A Critical Review on Recent Developments in Advanced Super-capacitors

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Abstract

Supercapacitors, also known as ultracapacitors, have emerged as a promising next-generation energy storage technology, offering rapid charge-discharge capabilities, high power density, and exceptional cycle life. While they operate on principles similar to conventional capacitors, their enhanced performance is attributed to advanced electrode materials with high surface area and ultra-thin dielectric layers. The key components of a supercapacitor—electrodes, current collectors, separator, electrolyte, and binder—collectively determine its efficiency, with the electrode material playing a central role. Recent advancements in materials science have introduced the use of conducting polymers, carbonaceous nanostructures, and transition metal oxides to enhance energy and power densities. Simultaneously, innovations in electrolyte formulations, including the use of ionic liquids and gel polymers, have expanded the operational voltage window and thermal stability. These developments have broadened the application of supercapacitors across various sectors, including aerospace, electronics, and increasingly, biomedical and veterinary diagnostics. In veterinary medicine, the integration of supercapacitors into diagnostic tools such as CT scanners, sonography, and MRI systems offers enhanced portability, reliability, and energy efficiency. This paper reviews the fundamental working principles, recent material innovations, and the growing role of supercapacitors in modern veterinary diagnostics, highlighting their potential to transform portable and high-performance diagnostic technologies.

Keywords: Capacitor, Super-capacitors, Magnetic Resonance Imaging, CT-Scan, Veterinary Medicine

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1.1 Introduction

Since ancient times, human civilization has experienced continuous growth and advancement, driven by the increasing demand for energy to power tools, technology, and infrastructure [1–4]. In the modern era, this demand has surged dramatically due to rapid industrialization, urbanization, and the proliferation of smart, flexible, and miniaturized electronic devices. The global population continues to rise, accompanied by a corresponding increase in energy consumption. With the introduction of new and intelligent

technologies in areas such as healthcare, communication, and transportation, the reliance on efficient and portable energy storage systems has become more critical than ever [5–7].

To address these challenges, there is a growing interest in developing high-performance energy storage devices that are compact, lightweight, environmentally friendly, and capable of fast charge-discharge cycles. Among the various solutions available, **supercapacitors** (also known as ultracapacitors) have emerged as a highly promising technology due to their unique advantages over conventional batteries and capacitors. These advantages include high power density, rapid energy delivery, long cycle life, low maintenance requirements, and minimal environmental impact [8–10].

The global energy crisis and the harmful effects of fossil fuel consumption—such as greenhouse gas emissions, climate change, and resource depletion—have also intensified the shift toward renewable and sustainable energy sources, including solar, wind, tidal, geothermal, and hydropower [11–13]. However, the intermittent nature of these sources poses a significant challenge to consistent energy supply, highlighting the need for efficient and reliable **energy storage solutions**. In this context, supercapacitors serve as a crucial bridge between traditional capacitors and rechargeable batteries, combining fast energy delivery with moderate energy storage capacity [14–15].

Supercapacitors are already finding applications across various industries, from powering mobile phones and wearable health monitoring systems to supporting electric vehicles, micro-sensors, and aerospace technologies. Wearable microsystems, in particular, are increasingly being integrated into consumer electronics and medical diagnostics, offering continuous real-time monitoring of physiological parameters such as heart rate, ECG, body temperature, and activity levels [16–18]. These applications demand compact, high-performance energy sources, and supercapacitors meet this demand through their ability to provide instant power in short bursts and recharge quickly.

At the core of supercapacitor technology lies the development of advanced materials and innovative device architectures. Recent research has focused on a variety of electrode materials—ranging from carbon-based nanostructures like graphene and carbon nanotubes, to pseudocapacitive materials such as transition metal oxides (e.g., MnO_2, RuO_2, NiO) and conductive polymers (e.g., polyaniline, polypyrrole). Furthermore, advancements in electrolyte design, including the use of ionic liquids and solid-state gel polymers, have expanded the operational voltage range, energy density, and temperature stability of supercapacitors [19–21].

Despite these advantages, challenges such as limited energy density, cost of high-performance materials, and integration with existing electronic systems remain. Ongoing research is directed toward the exploration of **novel materials**, **hybrid systems**, **nanostructured architectures**, and **flexible or wearable formats** that could overcome these barriers and enable broader adoption of supercapacitor technology.

In light of the growing demand for efficient energy storage systems and the shift toward sustainable energy solutions, this paper presents a comprehensive overview of supercapacitors—emphasizing their fundamental working principles, recent advances in materials and fabrication methods, and their emerging applications in portable and diagnostic devices, particularly in the context of veterinary and medical technologies.

Supercapacitors, also known as ultracapacitors or electrochemical double-layer capacitors (EDLCs), are advanced energy storage devices capable of storing significantly more energy per unit mass or volume compared to conventional electrolytic capacitors—typically 10 to 100 times more [23]. They function by storing electrical energy at the interface between an electrode and an electrolyte, where a double-layer of charge is formed. Unlike traditional batteries that rely on slow faradaic redox reactions, supercapacitors store energy primarily through rapid electrostatic processes, resulting in high power densities and extremely fast charge-discharge cycles.

At their core, capacitors are passive electronic components made up of two or more conductive plates separated by a dielectric (insulating) material [24]. When a direct current (DC) voltage is applied across a capacitor, an electric field is established between the plates, causing a positive charge to accumulate on one plate and a corresponding negative charge on the other. This process continues until the voltage across the plates equals the applied voltage.

The geometry and configuration of capacitor plates—including square, rectangular, cylindrical, or spherical shapes—are optimized depending on application-specific requirements such as energy density, voltage rating, and form factor [25]. In supercapacitors, this concept is extended by using high surface area materials (e.g., activated carbon, graphene) to maximize charge storage, and by reducing the separation between charges to the molecular scale using electrolytes and porous electrode architectures.

There are two primary mechanisms of energy storage in supercapacitors: electrochemical double-layer capacitance (non-faradaic) and pseudocapacitance (faradaic). While EDLCs store energy through charge separation at the electrode–electrolyte

interface, pseudocapacitors involve fast redox reactions, allowing even greater energy densities. Hybrid supercapacitors combine both mechanisms to further optimize performance.

Supercapacitors offer several distinct advantages over traditional energy storage devices, including:

- **High power density**, allowing for rapid energy delivery.
- **Long cycle life**, often exceeding one million charge-discharge cycles.
- **Fast charge and discharge times**, ranging from seconds to minutes.
- **Wide operational temperature range**, typically from -40°C to 70°C [27].
- **Low maintenance**, compact size, and lightweight packaging.
- **Environmentally friendly**, as many supercapacitors contain no toxic or hazardous materials.

Despite these advantages, supercapacitors also present certain limitations. The most significant drawback is their lower energy density compared to batteries, which limits their use in applications requiring long-term energy storage. Additionally, voltage balancing and management are required in series configurations due to cell-to-cell variations.

Among modern energy storage and conversion technologies, electrochemical supercapacitors and fuel cells are considered revolutionary. Fuel cells offer high energy density but suffer from slower response times and higher costs. Supercapacitors, on the other hand, excel in applications requiring quick bursts of energy, such as regenerative braking in electric vehicles, backup power for electronics, and energy buffering in renewable energy systems.

Ongoing research is focused on improving the energy density of supercapacitors through the development of novel materials, including transition metal oxides, conductive polymers, metal-organic frameworks (MOFs), and emerging two-dimensional materials such as MXenes. Additionally, innovations in electrolyte chemistry, including ionic liquids and gel polymer electrolytes, are enhancing voltage windows and thermal stability, enabling broader practical deployment.

Thus, supercapacitors represent a key component in the evolving landscape of energy storage technologies, offering a sustainable and high-performance solution for modern electronic, automotive, aerospace, and biomedical applications [28].

Table No. 1: Comparative Study of Energy Storage Devices

Category	Advantage	Disadvantage
Super-capacitor	High power density Long cycle life Fast charging speed Good low temperature performance High current discharge ability Super low temperature characteristic Simple charging and discharging circuit Convenient detection	Low energy density
Lithium ion battery	High working platform High energy density Long cycle life Fast charge and discharge Good safety performance no pollution and no memory effect Small self-discharge Large temperature range	Poor rate performance Low coulomb efficiency poor cycle stability
Sodium ion battery	Energy density comparable to lithium ion battery	There is technical threshold for sodium ion batteries is

	Rich in sodium Strong stability High safety Long service life Wide range of applications Easy access to raw materials Waste recycling process is simple and pollution free Fast charge and discharge Sodium ion batteries have no over discharge characteristics, allowing sodium ion batteries to discharge to 0V	higher than lithium ion batteries. The comprehensive electrochemical performance is worse than that of lithium ion batteries.

As global development advances, economies remain fundamentally dependent on diverse energy sources. At present, many countries rely heavily on imported crude oil; for instance, India imports nearly 80 % of its crude oil requirements [29]. These finite fossil reserves are being depleted at an alarming rate, and their combustion underpins most motor-vehicle transportation, releasing gases and particulate matter that exacerbate air pollution and drive the greenhouse effect and global warming. In this context, the transition to renewable energy sources—such as wind, solar, hydro, tidal, geothermal, and biomass—is imperative, offering cleaner, more sustainable, and ultimately more cost-effective solutions [30]. Equally important is the development of efficient thermal and electrical energy storage systems to buffer the intermittent nature of many renewables and ensure a stable supply.

Recognizing these challenges, governments and research institutions worldwide are intensifying efforts to develop next-generation energy technologies. In India, agencies such as the Bureau of Energy Efficiency (BEE) and the Petroleum Conservation Research Association (PCRA) are leading initiatives to improve thermal conversion efficiency, promote energy conservation, and facilitate the deployment of renewables [31]. Similarly, in the United States, federal policies and incentives have spurred the rapid growth of renewable installations—wind energy alone accounted for approximately 9 % of total electricity generation in recent years [32]. Such concerted actions underscore the global commitment to diversifying energy portfolios, reducing reliance on depleting fossil fuels, mitigating environmental impact, and securing a sustainable energy future.

The distinction between conventional and non-conventional source of energy is as below [32]:

Table No.2: Distinction Between Conventional and Non-Conventional Devices

Conventional Source of Energy	Non-conventional Source of Energy
These sources of energy are also known as non-renewable source of energy	These sources of energy are also known as renewable source of energy
They are used for both commercial and industrial purposes	They are mainly used for household purposes
They are responsible for pollution	These are not responsible for any type of pollution
Examples: coal, petroleum, gasoline etc	Examples: solar energy, wind energy, tidal energy etc

Researchers today are pioneering hybrid energy-storage systems that combine the best attributes of batteries and supercapacitors by exploiting novel nanomaterials—such as MXenes, metal–organic frameworks (MOFs), and conductive polymer composites—to tailor charge-storage mechanisms and boost both energy and power

densities. At the same time, advanced fast-charging protocols and power-management electronics have been developed to significantly reduce recharge times without compromising device longevity. Supercapacitors themselves are electrochemical energy-storage devices characterized by exceptionally high power density but relatively low energy density. In contrast, conventional batteries consist of one or more electrochemical cells in which chemical energy is converted to electricity via redox reactions at the electrodes: as current flows, the anode is oxidized and the cathode reduced. Over many cycles, electrode surface irregularities and the buildup of reaction by-products degrade battery capacity, and the exothermic nature of discharge poses thermal-management challenges, limiting operating temperature and peak power output.

The 2019 Nobel Prize in Chemistry underscored the transformative impact of lithium-ion batteries—members of a broader class of electrochemical devices that provide on-demand electrical energy by converting stored chemical energy. Supercapacitors, often termed “next-generation” capacitors, bridge the gap between conventional electrolytic capacitors and rechargeable batteries: they accept and deliver charge far more rapidly than batteries, tolerate hundreds of thousands to millions of charge–discharge cycles, and require only simple, robust circuitry for monitoring and control. As a result, they are routinely deployed alongside batteries to compensate for the latter’s slower power delivery, ensuring stable voltage during peak loads (e.g., in regenerative-braking systems, power-backup modules, and microgrid applications).

Recent advances have focused on overcoming the intrinsic limitations of supercapacitors—namely their lower energy density and limited cell voltage—through strategies such as asymmetric device architectures (pairing carbon-based EDLC electrodes with high-capacity pseudocapacitive materials), redox-active electrolytes, and solid-state or hybrid gel electrolytes that expand voltage windows and improve safety. Flexible and wearable supercapacitors, enabled by printing and fiber-spinning techniques, are now demonstrating stretchability and biocompatibility for integration into smart textiles and implantable medical sensors. Three-dimensional porous electrode scaffolds, fabricated via templating or 3D printing, further increase accessible surface area and ion-transport pathways, driving both power and energy enhancements. Collectively, these innovations are steering supercapacitor technology toward fully hybridized energy-storage platforms capable of meeting the rigorous demands of tomorrow’s electric vehicles, portable electronics, and distributed renewable-energy systems.

With advances in mechatronics, electric vehicles (EVs) have become increasingly viable alternatives to combustion-engine cars, relying solely on electrical energy rather than fossil fuels. EVs impose dual

demands on their energy-storage systems: very high power density for rapid acceleration and regenerative braking, and high energy density for extended driving range. Because no single storage medium excels equally at both, hybrid configurations that pair supercapacitors with batteries have emerged as a compelling solution. In such systems, supercapacitors handle peak power events —delivering instantaneous bursts of energy and capturing braking energy with minimal losses—while batteries supply the sustained energy required for cruising. Integrating supercapacitor units alongside battery packs in EV storage architectures offers several key benefits [39]:

- **Peak-power support:** Supercapacitors supply short, high-current discharges during acceleration, reducing strain on the battery.
- **Enhanced battery longevity:** By smoothing power demands, supercapacitors minimize deep discharge cycles, slowing battery degradation.
- **Faster charge/discharge:** Supercapacitors' rapid kinetics enable quick energy uptake during regenerative braking and rapid power delivery when needed.
- **Improved energy efficiency:** Load leveling between supercapacitors and batteries reduces overall system losses.
- **Thermal management:** Offloading high-power transients to supercapacitors helps maintain more stable battery temperatures.

Together, these advantages create more robust, efficient, and durable EV powertrains capable of meeting both the instantaneous and sustained energy needs of modern electric mobility.

1) To impart longer life cycle which make them suitable candidate for automobile application. A regular battery can handle around 2000-3000 charge and discharge cycle, while super-capacitors can usually sustain more than 1000000.

2) To improve overall drive efficiency, thereby increasing the driving range.

3) To reduce life cycle costs by extending the battery life.

4) To reduce capital costs by direct replacement of some batteries.

5) Super-capacitors imparts faster charge and discharge

6) Super-capacitors can be operated over a wide temperature range i.e. from -40^0C – to 70^0C.

7) low equivalent series resistance (ESR).

8) High power density due to high discharge currents.

9) It offers longer service and long life i.e. about 10-15 years compared to 5-10 years for Li-ion batteries. It offers virtually unlimited cycle-life and can be cycled millions of time.

Drawback of Super-capacitors:

1} The super-capacitors can be used in AC and higher frequency circuits.

2) Super-capacitors offer low energy density as compared to battery. This is about $1/5^{th}$ to $1/10^{th}$ the energy of the battery.

1.2 ENERGY Storage Devices.

According to the statement of first law of thermodynamics, energy of the universe is constant, i.e., total amount of energy in the universe is always conserved [40] . In other words, energy can neither be created nor destroyed; it can be transformed from one form into another. Also it is possible to store energy in a suitable form with minimum loss. Energy storage can be categorized in the following ways:

1. **Thermal energy storage (TES)** systems store and release energy by exploiting the temperature-dependent heat capacity of a storage medium. During periods of excess thermal input, the medium—such as water, molten salts, or phase-change materials—is heated (or cooled), thereby accumulating sensible or latent heat. When demand for energy arises, the stored thermal energy is subsequently recovered as the medium returns toward ambient temperature. A common implementation is the use of insulated water tanks: surplus heat (e.g., from solar collectors or waste-heat streams) is transferred to water, raising its temperature; this stored heat can then be dispatched for space heating, domestic hot water, or process heating when primary energy supply is limited [41]. Such TES strategies improve overall system efficiency, enable load-shifting, and facilitate the integration of intermittent renewable sources into heating and cooling networks.

2 **Electrical energy** storage encompasses techniques that capture, retain, and deliver electrical charge via electrostatic or electrochemical processes. Early observations of electricity date back to ancient Greece, where Thales of Miletus noted that rubbing amber with fur generated static attraction [42]. By the late 1600s, scientists routinely produced static charges by rubbing insulating materials—such as amber, sulfur, and glass—with cloth or fur, paving the way for systematic studies of electrical phenomena. In 1780, Luigi Galvani's experiments on frog legs led him to propose "animal electricity," but Alessandro Volta correctly attributed the effect to redox reactions between two dissimilar metals connected by a conductive medium. Volta's subsequent invention of the voltaic pile in 1800 marked the first true battery, establishing the foundational principles of electrochemical energy storage [42]. Parallel developments in dielectric materials transformed the Leyden jar into modern capacitors. These early milestones set the stage for today's diverse EES technologies—from high-energy-density batteries to high-power-density super capacitors—each optimized to meet specific applications' demands for energy capacity, power delivery, and cycle life.

Thermal energy storage is carried out with the support properties associated with the latent heat of various materials, while electrical energy is the majority resourceful form of energy. Storage devices are essential units that store electric energies produced by different sources. Storage devices takes an important part in the electricity storage system for households, the medium-size system for industrial/ commercial use., and the extra-large system for power plants and substation. Depending upon the mechanism of electrical charge storage, it is classified as:

1. Capacitors (Storage employing Electrostatic): Capacitance can be defined as that property of electric circuit that opposes the change in voltage. Capacitor stores the energy in the form of electricity and releases it when used in the circuit as current. The capacitors can be simply designed by using any two metal conductors separated by a dielectric constitutes. Thus there is development of an electric field between two charged plates. The unit of capacitance is Farad named after great scientist Michael Faraday [43].

C=q/v or

C=έ.έ0 A/d

Where A= Area in cm^2

^{έ} = dielectric constant

d= distance in cm

The dielectric constant is a medium which permits the establishment of lines of force between oppositely charged plates [44].

έ = $8.85* 10^{-12}$

Characteristic of Capacitance [45]:

(1) **Energy Absorption:** Capacitive energy absorption hinges on a capacitor's ability to store charge electrostatically: when a voltage VVV is applied across two conductive plates separated by a dielectric, equal and opposite charges ±Q±Q±Q accumulate, and the stored energy is given by E=-1/2CV2E= where C depends on the plate area, separation distance, and the dielectric's permittivity. This quadratic energy–voltage relationship means that increasing the voltage yields disproportionately more stored energy, limited only by the dielectric breakdown strength. Because no slow chemical reactions are involved, capacitors can absorb and discharge energy almost instantaneously, delivering exceptionally high power density ideal for pulse-power applications such as regenerative braking and power conditioning. Real-world performance, however, is tempered by dielectric losses—quantified by the loss tangent—that grow at higher frequencies when the dielectric cannot fully reorient, leading to heat generation and reduced effective capacitance. Traditional capacitors exhibit relatively low energy density compared to batteries, but advances in high-k ceramics, polymer composites, and nanostructured dielectrics are pushing these limits by enhancing permittivity without sacrificing voltage tolerance. Moreover, capacitors boast near-100 % coulombic efficiency and can endure millions of cycles with minimal degradation, while their reliance on physical rather than chemical mechanisms

affords broad temperature stability, low susceptibility to mechanical stress, and rapid response—attributes that make them indispensable in applications demanding fast, efficient, and durable energy storage.

(2) **Temperature co-efficient:** The temperature coefficient of capacitance refers to the degree to which a capacitor's capacitance value changes with temperature. This characteristic is crucial in determining the reliability and performance stability of capacitors under varying thermal conditions. Most dielectric materials used in capacitors exhibit some degree of temperature sensitivity, meaning their permittivity—and consequently, the capacitance—can increase or decrease with temperature. The temperature coefficient is usually expressed in parts per million per degree Celsius (ppm/°C) and may be positive, negative, or near-zero, depending on the dielectric material. For instance, Class I ceramic capacitors, such as those made with NP0 (C0G) dielectric, have very low temperature coefficients (typically ±30 ppm/°C), making them ideal for precision circuits and temperature-sensitive applications. On the other hand, Class II and III ceramics, like X7R or Y5V, have higher capacitance values but much larger and less stable temperature coefficients, sometimes exceeding ±15% over a standard operating range, which limits their use in high-precision environments. Electrolytic capacitors also tend to show a negative temperature coefficient, where capacitance decreases as temperature increases. These temperature-induced changes can affect timing circuits, filters, and oscillators, where accurate capacitance values are critical. In practical applications, engineers must consider these coefficients when designing circuits to ensure performance remains consistent over a device’s entire temperature range. Advanced materials and construction methods are increasingly being developed to create capacitors with minimal temperature variation, improving reliability in automotive, aerospace, and industrial electronics where wide thermal fluctuations are common.

(3) **Dielectric Absorption: It is** observed that absorption of charge is due to the dielectric polarization. When capacitor is discharged by a short circuit it is found to have charge after a short is removed. The residual energy left after discharge is an energy loss.

(4) **Power Factor:** The power factor of a capacitor is a key parameter that indicates the efficiency of energy usage in AC circuits and is defined as the cosine of the phase angle between voltage and current. In an ideal capacitor, the current leads the voltage by 90 degrees, resulting in a power factor of zero because no real power is consumed—only reactive power circulates in the system. However, in real capacitors, due to internal resistance, dielectric losses, and leakage currents, the current phase shift is slightly less than 90 degrees, giving rise to a small but measurable power factor. This is commonly expressed as the dissipation factor (DF) or loss tangent (tan δ), where a higher power factor reflects greater energy loss as heat. Power factor becomes particularly important in high-frequency or high-voltage applications where dielectric losses can significantly affect performance. Capacitors with low power factors (high losses) may cause overheating, reduce efficiency, and degrade over time. For instance, electrolytic and Class II/III ceramic capacitors typically exhibit higher power factors compared to Class I ceramic or film capacitors, which are designed for low-loss, high-efficiency applications. In power electronics and AC power systems, capacitors are often used to correct lagging power factors caused by inductive loads, improving overall energy efficiency. In such cases, power factor correction capacitors are selected for their low loss characteristics and stability under varying load conditions. Hence, understanding and managing the power factor of capacitors is essential for optimizing circuit performance, reducing energy losses, and ensuring long-term operational stability.

Cos Φ = R/z Thus it is a complex function of frequency, temperature, voltage, stress on dielectric material and

losses in conductor. Increase in power factor results in higher operating temperature when ac is applied. Its effect is to decrease the life.

(5) Ca**pacitor ratings:** At high frequency the maximum current permissible depends upon I^2R or heat that can be safely dissipated. At low frequency voltage rating is more important.

(6) **Temperature co-efficient:** Capacitors store electrons and are electrical devices. As temperature increases, there is change in capacitance. A temperature of 25 C is normally used as design temperature. Any deviation from this temperature changes the capacitance. It has been observed that rise in temperature increases the efficiency of capacitance. Temperature plays a crucial role in power capacity. High temperature breaks down insulation and lowers the rated working voltage. The properties of dielectric materials are affected by temperature.

(7) **Insulation resistance:** Insulation resistance is a critical characteristic of capacitors, representing the resistance offered by the dielectric material to the leakage current that flows through it when a voltage is applied. Ideally, a capacitor should block direct current completely, but in practical applications, a small amount of leakage current flows due to imperfections in the dielectric, and this is quantified by the insulation resistance, usually measured in megaohms (MΩ) or gigaohms (GΩ). A high insulation resistance is desirable, as it indicates minimal leakage and higher efficiency in energy storage. This property becomes especially important in timing, coupling, and storage applications, where even a small leakage current can result in voltage loss, timing inaccuracies, or data corruption over time. Insulation resistance is influenced by several factors including the type of dielectric material, capacitor construction, temperature, humidity, and the applied voltage. For instance, ceramic and film capacitors generally exhibit high insulation resistance, making them suitable for precision circuits, while electrolytic capacitors often show

lower insulation resistance due to their inherently conductive electrolyte. Over time, factors such as aging, thermal stress, and environmental conditions can degrade the dielectric and reduce insulation resistance, leading to increased leakage current and potential failure. Manufacturers often specify insulation resistance as a function of capacitance (e.g., product of capacitance and resistance in ohm-farads) to enable performance comparison across different capacitor types. Ensuring high insulation resistance is therefore essential for long-term stability, safety, and efficiency, especially in applications requiring low leakage, such as medical devices, aerospace systems, and high-precision electronics.

(8) **Time Constant:** The time constant of a capacitor, denoted by the Greek letter tau (τ), is a fundamental characteristic that defines how quickly a capacitor charges or discharges in a resistive circuit. It is mathematically expressed as $\tau = R \times C$, where R is the resistance in ohms (Ω) and C is the capacitance in farads (F). The time constant represents the time it takes for the voltage across the capacitor to reach approximately 63.2% of its final value during charging, or to decay to about 36.8% of its initial value during discharging. This behavior follows an exponential curve and is crucial in designing and analyzing timing circuits, filters, and transient response systems. A large time constant means the capacitor charges or discharges slowly, which is desirable in applications like smoothing filters or timing delays. Conversely, a small time constant allows for rapid voltage changes, useful in high-speed switching or pulse circuits. The time constant also plays a vital role in determining how a system responds to changes in input, influencing stability and responsiveness. In real-world applications, factors such as temperature, dielectric losses, and leakage currents can affect the effective time constant. Accurate calculation and control of the time constant are essential for circuit performance, especially in analog signal processing, control systems, and communications. Understanding and applying the concept of time constant enables engineers to fine-tune electronic behavior and

achieve precise control over signal timing, making it a cornerstone of capacitor-based circuit design.

(9) **Capacitive reactance and impedance:** The opposition to flow of electron is known as resistance. When DC voltage is applied then there is rejection of dielectrics to accept electrons and remain constant for a given time. When AC voltage is applied then capacitive reactance opposes the flow of electrons during charging and discharging.

The dielectric constants and power factors of some common dielectric materials

Table No. 3: Comparative Study of Dielectric Materials

Dielectric Material	**Dielectric constant**	**Power factor**
Air	1.0001	0
Aluminium oxide	10.0	10.0
Ceramic	12 to 40* 10^4	0.001 to 0.0001
Glass	7.6	0.06
Kraft paper	4.0	3.0
Mica	6.85	0.02
Vacuum	1.0	0

Paper capacitors: Paper capacitors are traditional passive electronic components that utilize paper as the dielectric material placed between two conductive metal foils, typically aluminum, which are then rolled into a cylindrical shape and impregnated with wax or oil to improve insulation and moisture resistance. These capacitors were widely used in early electronic devices due to their simplicity, high voltage ratings, and low cost. Despite their relatively large size, high leakage current, and sensitivity to humidity, they offered good mechanical strength and reliability for coupling, decoupling, and power applications in radio and television circuits. Over time, paper capacitors were largely replaced by more compact and efficient capacitor types such as ceramic, film, and electrolytic

capacitors, which offer improved performance in terms of size, leakage resistance, and stability. However, paper capacitors are still employed in specific applications such as vintage electronic restorations, industrial high-voltage circuits, and some military-grade devices where their ability to withstand voltage surges and operate reliably under fluctuating conditions is valued. Recent interest in sustainable electronics has revived research into paper-based dielectrics, especially when combined with nanomaterials and bio-compatible polymers, potentially opening new avenues for eco-

become increasingly important, the study and development of advanced paper capacitors may contribute to greener and more sustainable electronic technologies in the future [46].

App**lication of Capacitors:** As the name indicates the main purpose of the capacitor is to store the energy. However, the internal resistance of capacitance will cause different charge – discharge time cycles.

 Energy Storage – Capacitors store electrical energy for use in circuits where quick energy discharge is needed (e.g., camera flashes, defibrillators).

 Power Conditioning – Used to smooth output from power supplies by filtering noise and voltage spikes.

 Signal Coupling and Decoupling – Capacitors pass AC signals between circuit stages while blocking DC, and decouple unwanted AC from DC power lines.

 Timing Circuits – Combined with resistors to create RC time constants, they control timing in oscillators, clocks, and delay circuits.

 Motor Starters – In AC induction motors, capacitors improve starting torque and running efficiency.

 Power Factor Correction – Used in industrial power systems to improve power factor and reduce energy losses.

 Tuning Circuits – In radios and TVs, capacitors are used in LC circuits to select desired frequencies.

 Filter Circuits – Essential in analog and digital filters to remove unwanted frequencies or noise.

 Surge Protection – Absorb high-voltage spikes to protect sensitive electronic components.

 Flash Photography – Capacitors store energy to quickly release it for camera flash operation.

 Touch Sensors – Used in capacitive touchscreens and proximity sensors.

 Audio Systems – Improve audio quality by filtering low frequencies in crossovers for speakers.

 Inverter Circuits – Help in DC to AC conversion by stabilizing voltage levels.

 Medical Devices – Used in implantable devices like pacemakers and defibrillators for controlled energy delivery.

 Electric Vehicles – Capacitors assist batteries in providing quick bursts of power during acceleration.

Batteries and fuel cells (Storage employing Chemical): These are the mobile source of power that makes many modern conveniences possible.

2. A super-capacitor (Storage employing Electrochemical)

   In the modern period electrical energy is an enormous and flexible form of energy that is universally used. The energy can be easily stored in the form of chemical energy, but it is difficult to store energy in the form of electrical energy [47]. The chronological development in the energy storage devices can be ascribed as batteries, capacitors and super-capacitors. Each device has its own merit and demerit. Batteries have a large energy density, but it requires more time for the charging process. The capacitors can be charged up instantly, but the charge storage capacity is smaller. The super-capacitor works as the connecting link between batteries and capacitors [48]. The drawback of batteries and capacitors can

be overcome by the super-capacitors. Super-capacitors are high-energy electrochemical capacitors with ample higher capacitance than a conventional capacitance of the same size [49]. The super-capacitors are also known as ultra-capacitors, electrical double layer capacitors, gold capacitors etc. [50]. The super-capacitors are correct alternative to conventional battery storage systems as they offer a much higher power density. The super-capacitors store energy in electrostatic field by ion polarization. The energy density of super-capacitor is considerably low as compared to battery [51].

There are mainly energy storage systems such as conventional capacitors, supercapacitors, and batteries. The performance of various energy storage devices like batteries, super-capacitors and capacitors can be plotted together is known as Ragone plot as shown in Figure 1. Here the power density is plotted along the Y axis measured in Watt per kilogram ($W.kg^{-1}$), and the energy density along the X-axis, measured in Watt-hours per kilogram ($Wh.kg^{-1}$) [52]. The batteries and super-capacitors store electrical energy in different ways. In batteries two electrical terminals known as electrodes are separated from each other by means of chemical substances known as electrolytes [53]. When a potential is applied between anode and cathode, a chemical reaction occurs between these two electrodes and electrolyte solution. As a result, the chemical nature of the substance inside the battery is altered, releasing electrical energy. The Ragone plot is a plot being used to compare the performance of various energy storage device. In other words, the Ragone plot illustrates storage devices' specific power density and energy density. In Ragone plot specific energy is plotted verses specific power. Normally horizontal and vertical axes are in logarithmic scale and the performance of different energy storage devices can be compared. This type of plat was first time used to determine the performance of batteries. Also, it was found that the supercapacitors

occupied the region between conventional capacitors and batteries [54].

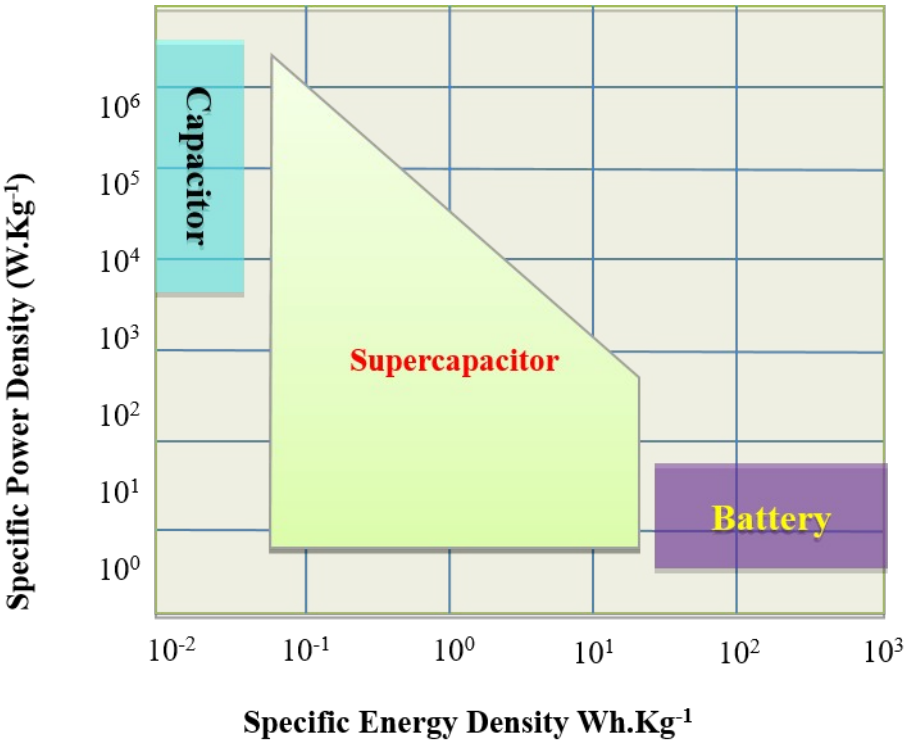

Fig. 1: Ragone plot-power density versus energy density for various electrical energy storage systems [22].

The performance of electrochemical super-capacitors is primarily determined by two key parameters: energy density and power density. Higher values of both these characteristics are essential for optimal device performance. Energy density reflects the amount of energy the device can store, while power density indicates how quickly that energy can be delivered. Achieving a balance between these two factors is crucial, as enhancing one often compromises the other. To address this challenge, researchers are continuously exploring innovative strategies and advanced materials to significantly increase the energy density of super-capacitors without sacrificing their inherent high power density. This includes the development of novel electrode materials, nanostructured architectures, hybrid systems, and the use of advanced electrolytes. Through such advancements, the goal is to create high-performance super-capacitors that combine the rapid charge-discharge capabilities of capacitors with the high energy storage potential of batteries,

thereby expanding their applicability in a wide range of fields from portable electronics to electric vehicles and renewable energy systems. [55].

Super-capacitors offer significantly higher charging and discharging cycles compared to conventional batteries, making them highly durable and efficient for long-term use. Modern advancements have led to the development of super-capacitors with exceptionally high capacitance values—ranging up to several thousand farads—and operating voltages of up to 3V, which are now commercially available. These devices are characterized by very low equivalent series resistance (ESR), enabling them to deliver high instantaneous power, which makes them ideal for applications requiring rapid energy bursts. In addition to their impressive power-handling capabilities, electrochemical super-capacitors also offer several other advantages, including extended shelf life, high energy efficiency, and the ability to undergo repeated charge and discharge cycles with minimal degradation. Their performance remains stable over time, unlike batteries which tend to lose capacity with usage. This resilience makes super-capacitors highly suitable for applications in backup power systems, electric vehicles, regenerative braking systems, and various portable electronic devices where both high power output and long operational life are essential. [56]. Such type of super-capacitors can work at shallow temperatures. On account of such advantages, super-capacitors are widely employed for substituting/assisting batteries for various applications like electric vehicles, traction, micro-grids, aeronautical systems, energy-harvesting systems in wireless nodes, and so on. In spite of these working advantages, the design of a Super-capacitor based system faces several challenges. The common challenge observed for super-capacitors is the porous structure of the electrodes used for super-capacitors, diffusion effects of the ions, and charge storage on the electrode-electrolyte double-layer interface [57].

The fundamental construction of a super-capacitor is depicted in Fig. 2, where two conductive electrodes are separated by a narrow gap. This gap is filled with a dielectric material, which plays a crucial role in determining the performance characteristics of the device. A wide variety of dielectric materials are utilized depending on the application requirements, each offering distinct electrical and thermal properties. Commonly used dielectric materials include mica, air, oiled paper, glass, porcelain, and titanates. These materials are

chosen based on factors such as dielectric constant, thermal stability, and breakdown voltage. The proper selection and optimization of the dielectric not only enhance the energy storage capability of the super-capacitor but also improve its reliability, efficiency, and operational lifespan. [58]. The conductive plates of super-capacitors are typically made from metals, while the dielectric materials used are non-metallic and inherently insulating. Super-capacitors are charged when an external potential difference is applied across the two plates, which act as electrodes. During the charging process, positive charges accumulate on one plate, while the other plate collects negative charges. Once the external voltage is removed, the positive and negative charges remain on their respective electrodes, effectively storing electrical energy. This process of charge separation is what enables capacitors to store energy. While capacitors excel in certain applications due to their rapid charge and discharge capabilities, they are often considered less efficient than batteries in terms of energy storage capacity. This is because capacitors generally cannot store as much electrical energy as batteries. However, capacitors have a notable advantage over batteries, as they do not contain toxic chemicals, making them more environmentally friendly and safer to use. [59].

Construction of capacitance: Capacitance is the electrical property of a capacitor, representing its ability to store an electrical charge on its two plates. The unit of capacitance is the farad, named after the British physicist Michael Faraday. In super-capacitors, the electrolyte solution plays a crucial role, containing both positively charged ions, known as cations, and negatively charged ions, called anions. When the super-capacitor is charged, the cations are attracted to the negative electrode, while the anions are drawn toward the positive electrode. This movement of ions facilitates the storage of electrical energy, allowing the capacitor to maintain a high energy density and charge retention, contributing to the efficient performance of the super-capacitor as shown in Figure 2.

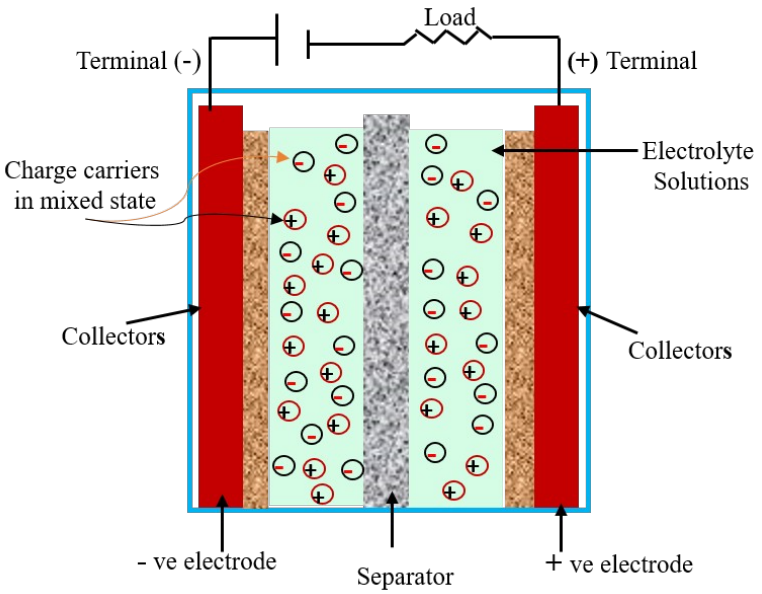

Fig. 2: General construction of Super-capacitor [22]

The structural components of super-capacitors are illustrated as: two electrodes, two current collectors, a separator, binder and electrolyte solution [60] .

(a) Electrodes:

The selection and fabrication of electrode materials are critical factors in enhancing the performance of super-capacitors. The ideal electrode material should exhibit thermal stability, high specific surface area (SSA), corrosion resistance, excellent electrical conductivity, appropriate chemical stability, and suitable surface wettability. These properties ensure that the electrodes can efficiently store and release charge while maintaining long-term performance. Super-capacitor electrodes are commonly made from a variety of materials, including activated carbon, metal nanoparticles, and other advanced carbon-based structures. To maximize capacitive performance, electrodes are designed to be porous, which increases the available surface area for charge storage. This feature enables the super-capacitor to store a greater number of charge carriers, thereby increasing its capacitance. Common materials used for electrode fabrication include activated carbon, carbide-derived carbons, carbon aerogels, carbon nanotubes, carbon fiber cloth, metal oxide nanomaterials, and polymers. Typically, super-capacitors consist of two electrodes: a positive electrode and a negative electrode. By selecting and

optimizing these materials, researchers can significantly improve the energy storage and power delivery capabilities of super-capacitors, making them more effective for a wide range of applications [61].

(b) Current Collectors

The current collectors in super-capacitors are typically made from aluminum foil, though other metals such as copper may also be used. These current collectors serve an essential role in connecting the electrodes to the terminals of the capacitor, allowing for the efficient transfer of electrical current. In addition to facilitating electrical conductivity, current collectors also provide structural support for the activated carbon electrodes. Despite their critical function, current collectors have not received as much research attention as other components like electrodes, primarily because well-established materials like aluminum and copper foils are already available and perform reliably. In a super-capacitor, there are two current collectors—one for the positive electrode and another for the negative electrode—ensuring that each electrode can efficiently deliver or receive electrical charge during charging and discharging cycles. The proper selection and optimization of current collector materials, though often overlooked, remain important for maximizing the performance and longevity of super-capacitors [62].

(c) Separator

The separator in a super-capacitor serves as an insulating layer between the two electrodes, ensuring that the device does not experience a short circuit. Its primary functions include preventing direct contact between the electrodes while allowing the flow of charge carriers during the charging and discharging processes. Additionally, the separator helps to store the electrolyte within its pores, contributing to the efficient movement of ions between the electrodes. The separator is typically made from materials like Kapton, known for its excellent electrical insulation properties and thermal stability. It is very thin, often resembling paper in texture, which helps minimize resistance to ion flow. While the separator provides essential insulation, it is designed to be permeable enough to facilitate the passage of ions, thus supporting the electrochemical reactions necessary for the super-capacitor's operation. The material and design of the separator are crucial in ensuring the super-capacitor's performance, longevity, and safety [63].

(d) Electrolyte Solution:

The electrolyte plays a critical role in the performance of super-capacitors by influencing their efficiency, stability, and energy storage capacity. An ideal electrolyte should offer a wide voltage window, high electrochemical stability, high ionic concentration, low toxicity, and low viscosity. Aqueous electrolytes, such as mineral acids and alkali solutions, are commonly used due to their effectiveness in many applications. However, for super-capacitors requiring higher energy density, organic electrolytes or ionic liquids are preferred. Electrolytes can be classified into three main categories: (1) Aqueous electrolytes, (2) Organic electrolytes, and (3) Ionic liquid electrolytes. Aqueous electrolytes have a maximum working voltage limit of 1.23V, while organic and ionic liquid electrolytes provide a broader working voltage window but often come with higher internal resistance. For wearable electronic devices, solid-state polymer electrolytes are typically used. These are created by mixing an electrolyte solution with a polymer matrix, such as polyvinyl alcohol, poly-vinylidene difluoride, or polyethylene oxide. Acetonitrile and polypropylene carbonate are sometimes used as electrolytes in super-capacitors. Organic electrolytes, such as tetrafluoroborate in acetonitrile or propylene carbonate, are preferred for applications requiring high energy storage due to their better performance compared to aqueous electrolytes. Recently, ionic liquids have gained popularity as electrolytes. These are organic salts composed of large cations and inorganic anions, which remain in liquid form at room temperature or even at lower temperatures. Common ionic liquids for super-capacitor applications include imidazolium, pyrrolidinium, pyridinium, piperidinium, and tetra-alkylammonium cations, paired with anions such as Cl-. Lastly, the binder in a super-capacitor plays a crucial role in keeping the active materials attached to the electrodes in the electrolyte solution. The binder type and content significantly affect the super-capacitor's performance, with polyvinylidene fluoride being one of the most commonly used binders [64].

Working Principle of Super-capacitor: Super-capacitors, also known as ultra-capacitors or electrochemical capacitors, utilize high surface area electrode materials and thin electrolytic dielectrics to achieve capacitance values several orders of magnitude larger than conventional capacitors. These devices offer significantly higher specific power and

longer cycle lifetimes compared to most rechargeable batteries, including lead-acid, lithium-ion (Li-ion), and nickel-metal hydride (NiMH) batteries. When it comes to charging and discharging super-capacitors, there are two primary methods. The first involves charging or discharging at a constant cell voltage while recording the cell current over time. The second method entails charging or discharging at a constant current, with the cell voltage being recorded as it changes over time. Both methods are commonly employed depending on the specific application and requirements for performance.

(a) Charging of process:

When a potential difference is applied across the electrodes of a super-capacitor, the electrolyte solution, which contains both positive and negative ions, begins to charge. However, care must be taken during this process, as applying a higher potential than the specified limits can damage the components. As the potential difference is applied, the electrodes attract oppositely charged ions from the electrolyte. The positive electrode (anode) attracts negatively charged ions, while the negative electrode (cathode) attracts positively charged ions. This results in the formation of two distinct layers: a layer of positive ions near the cathode and a layer of negative ions near the anode. The arrangement of electrical charge carriers in these two layers is referred to as the Electrical Double Layer (EDL), a key characteristic of Electrical Double Layer Capacitors (EDLC). This mechanism is crucial for the functioning of super-capacitors, enabling them to store energy efficiently [65]. The process is illustrated in Figure 3a.

(b) Discharging process:

Self- discharge is known to have considerable adverse effects on the performance and applications of electro-chemical super-capacitor. The super-capacitors are prone to self-discharge, which is most often measured as a voltage decrease with time under operation. When we connect a load across the Supercapacitor, the electrodes cannot attract the ions, and the ions start distributing through the electrolyte solutions and go to the mixed state. The discharging of the Supercapacitor can be diagrammatically represented in the Figure 3b.

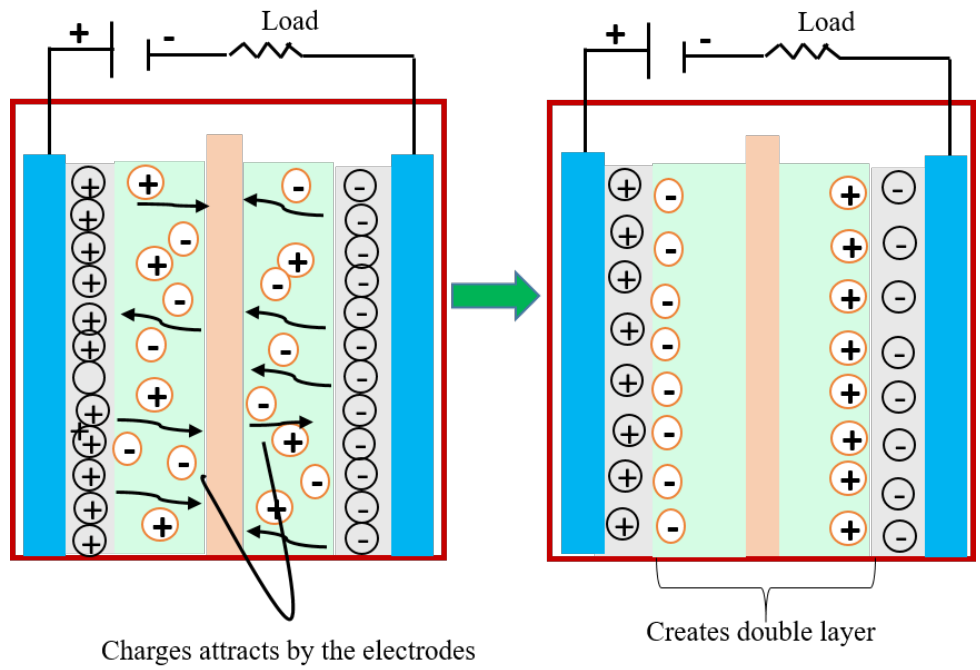

Fig. 3a: The charge process of Super-capacitor [22].

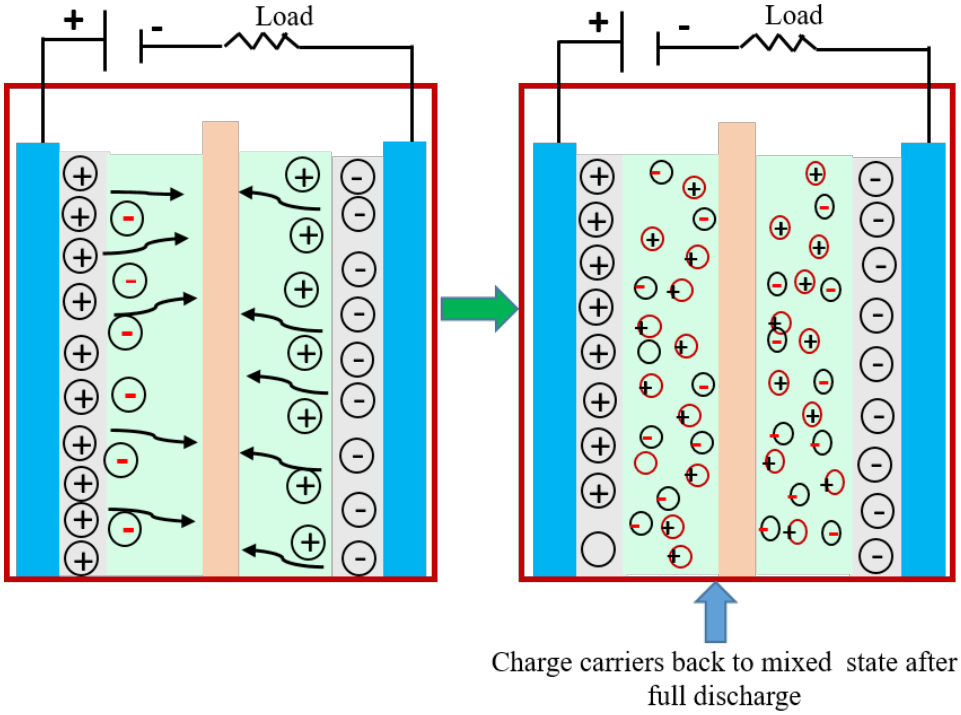

Fig. 3b: Discharge process of Super-capacitor [22]

Super-capacitors are generally distinguished from ordinary capacitors in two main ways: 1) The electrodes of super-capacitors are porous, providing a much larger surface area compared to conventional capacitors. This increased surface area allows for a higher capacitance, enabling super-capacitors to store more charge. 2) Additionally, the separation between

the two electrodes in a super-capacitor is extremely small, typically on the order of angstroms, which is much smaller than the separation in conventional capacitors. This reduced separation contributes to the higher energy storage capacity and efficiency of super-capacitors [66]. Due to the large surface area obtained by coating powders, activated charcoal enhances the storage capacity. In an ordinary capacitor, the plates are separated by a comparatively thick insulator whose behavior can be modified in an electric field called a dielectric, e.g., mica (a ceramic), a thin plastic film, or even simply air. When the capacitors are charged, the positive charge is induced on one electrode whereas the other electrode acts as negative terminal. Because of this, field polarization of the dielectric occurs, so its molecules align in the opposite direction in the applied field and reduce its strength which is responsible for the storage of charge on the plates in minimum Voltage [67]. The discharge curve of super-capacitor is linear, so it looks like a straight line.

The energy density and power density of the energy storage device can be calculated by equations as shown below:

$$E=\frac{1}{2}CV^2 \quad (1)$$

$$P=\frac{V^2}{4\times ESR} \quad (2)$$

Where,

E - Energy density

P - Power density

C- Specific capacitance

V- Operating potential window

ESR-Equivalent series resistance

As per the above equation, it is evident that the energy density increases significantly from capacitors to batteries, while there is a corresponding decrease in power density. Conventional capacitors exhibit higher power density, whereas batteries and fuel cells are known for their higher energy density. Therefore,

super-capacitors exhibit intermediate properties, combining aspects of both capacitors and batteries, and effectively serve as a bridge between these two energy storage devices. This unique balance allows super-capacitors to deliver high power output with relatively moderate energy storage capacity, making them ideal for applications requiring rapid bursts of energy.

1.3 DEVELOPMENTAL scenario of Super-capacitors

The energy conversion and storage is the fundamental pillar of modern society driven by the mutual promotion between environmental aspects and economical point of view [68]. After the invention of super-capacitor, so many modifications in their fabrication process has been incorporated keeping in mind for commercialization towards practical applications. Eisenberg and Rothenberg discovered the super-capacitor material during sideline experiment. The first super-capacitor was designed in the late 1950s using activated charcoal as the plates. The capacitor effect was discovered as early as in 1745, which consists of two conductor foils and the gap is filled with dielectric material. Such type of capacitor provides minimal energy, which is less than 360 joules per kilogram in energy density and with a unit of microfarad only. When a potential difference is applied cross the two electrodes of a capacitor, the opposite ions gets accumulated on the surface of electrodes bearing the opposite charges [69]. Hence the capacitance can be represented in the form of mathematical equation as below:

$$C = A/t \quad (3)$$

In conventional capacitors, the capacitance (C) is directly proportional to the surface area (A) of each electrode and inversely proportional to the thickness (t) of the electrical double layer. The concept of storing electrical charge at the interface between a metal and an electrolytic solution has been studied by chemists since the 19th century. However, it was only in 1957 that practical applications of double-layer capacitors began, with General Electric (GE) filing a patent for an electrolytic capacitor using porous carbon electrodes. In

standard capacitors, the separation between plates ranges from 10 to 100 microns, whereas in super-capacitors, the separation between the plates is in the range of thousandths of a micron. The patent, however, acknowledges certain limitations, stating that "it is not precisely known what occurs when these devices are used as energy-storing devices." This marks the beginning of super-capacitor technology, which has since evolved significantly, utilizing advanced materials and designs to improve energy storage and efficiency. [70]. However, it was believed that carbon pores are responsible for energy storage, and the capacitor exhibited exceptionally high capacitance

1.4. Need for Supercapacitors:

The growing threat of pollution and the depletion of oil reserves have prompted the search for alternative high-power energy sources, with super-capacitors emerging as a promising solution. Additionally, the rapid growth of portable electronic devices such as laptops, biological sensors, and chemical sensors has further fueled the need for efficient power sources. Currently, portable electronic devices predominantly rely on micro-batteries and micro-super-capacitors (MSC) to meet their power demands. Micro-super-capacitors, in particular, have garnered increasing interest in applications where long lifetimes and fast charge/discharge cycles are crucial. Their ability to deliver high power quickly while maintaining efficiency makes them ideal for a wide range of portable and energy-intensive devices [71For high-power applications, super-capacitors are essential energy storage devices. A capacitor stores energy in the form of a static electric field, allowing it to rapidly release the stored energy over a short period. This ability to deliver quick bursts of energy makes super-capacitors highly effective for applications that require high power output within brief intervals, such as in rapid charge/discharge cycles or when instantaneous energy delivery is critical [72]. Capacitors are commonly used in camera flashes to store energy and discharge it rapidly, producing a quick but bright flash of light to illuminate the scene. Capacitance is measured in farads, and

super-capacitors are emerging as a promising technology that is expected to play a significant role in meeting the energy storage needs of modern electronic devices and systems. The scientific community recognizes that super-capacitors are becoming increasingly attractive due to their ability to store energy efficiently. Micro-super-capacitors (MSC), in particular, can operate for extended periods with minimal capacitance loss, effectively addressing the issue of frequent replacements. MSCs offer higher power densities, a feature not achievable by micro-batteries, and have been observed to outperform micro-batteries in terms of practicality and efficiency across a wide range of applications. [73]. Modern micro-super-capacitors (MSC) can be broadly categorized into two main structures: (1) the conventional sandwich structure and (2) the in-plane interdigital structure. Studies have shown that interdigital coplanar electrode architectures often outperform conventional designs in terms of performance. The selection of electrode material is critical in the design and development of super-capacitors. Different materials exhibit distinct characteristics, but to achieve superior electrochemical performance, materials must possess good conductivity, a high specific surface area, and effective ion diffusion channels. With the rapid growth of portable electronic devices, which are becoming essential in today's society, the mobile energy storage market has expanded significantly. This sector is also innovating for future applications, such as flexible and printed electronics and displays. Flexible energy storage solutions are required to power these flexible devices, and electrochemical super-capacitors with high energy and power density are well-suited for this purpose [74]. To integrate super-capacitors with flexible electronics, they must be designed to be flexible and lightweight, often in sheet-like structures. The growing demand for soft, portable electronic devices, such as roll-up displays, electronic paper, and wearable systems for personal multimedia, necessitates the development of flexible energy storage devices. Flexible super-capacitors are becoming increasingly vital for

power source applications, as they combine the high power capabilities of traditional capacitors with the high specific energy of batteries. This unique combination makes flexible super-capacitors an ideal solution for emerging technologies in wearable and flexible electronics [75]. Super-capacitors have also appealed considerable interest because of ever increasing demand of electric vehicles, portable electronic devices and power sources for memory backup. The super-capacitor has been widely used as the electrical equivalent of flywheels in machine energy reservoirs that smooth out power supplies to electrical and electronic equipment.

1.5 CLASSIFICATION of Super capacitor

Super-capacitors can be classified into three types based on their energy storage mechanisms: 1) Electrochemical Double-Layer Capacitors (EDLCs), 2) Pseudocapacitors, and 3) Hybrid capacitors, which combine the characteristics of both EDLCs and pseudocapacitors. Each of these types utilizes a distinct charge storage mechanism, resulting in varying energy and power characteristics. EDLCs store energy through the electrostatic accumulation of charge at the interface between the electrode and electrolyte. Pseudocapacitors, on the other hand, store energy through fast redox reactions at the surface of the electrode material. Hybrid capacitors combine both mechanisms, often leveraging the strengths of both EDLCs and pseudocapacitors to achieve improved performance [76]. In the early stages, the concept of the electrochemical super-capacitor was based on the formation of an electrical double layer at the interface between a condenser and its electrolyte solution. Electrostatic and electrolytic capacitors are considered first and second-generation capacitors, respectively. With advancements in materials and technology, the third generation, known as super-capacitors, was developed. These super-capacitors leverage enhanced materials and mechanisms to significantly improve energy storage capacity and power delivery compared to their predecessors [77]. The detail systematic classification of super-

capacitors is illustrated as in Figure 4. SC is mainly classified into two types based on the charge storage mechanism: electric double-layer capacitors (EDLCs) and pseudocapacitor. The details information on different kinds of SC based on different storage mechanism are given below:

a) Electrochemical Double Layer Capacitors (EDLCs)

Von Helmholtz first introduced the concept of Electrochemical Double-Layer Capacitors (EDLCs) in the 19th century. The Helmholtz double-layer model describes the formation of two layers of opposite charges at the electrode-electrolyte interface, separated by an atomic distance. This model closely resembles the structure of a traditional two-plate capacitor, where the charges are accumulated on the surfaces of the electrodes [78]. Electrochemical Double-Layer Capacitors (EDLCs) are devices that store electrical energy by adsorbing ions from an electrolyte onto high surface area electrodes. These capacitors are known for their fast charging and discharging times, as well as their long cycle life, especially in comparison to batteries. The original Helmholtz model for EDLCs was later modified by Gouy and Chapman, who introduced the concept of a continuous distribution of electrolyte ions in the solution, driven by thermal motion. This distribution, referred to as the diffuse layer, extends beyond the initial electrostatic double layer. Subsequently, Stern combined the Helmholtz and Gouy-Chapman models, providing a more comprehensive view that recognized two distinct regions of ion distribution: the inner Helmholtz plane (or inner region) and the diffuse layer. This combined model helps explain the behavior of ions at the electrode-electrolyte interface in greater detail [79]. In the inner layer of an electrochemical double-layer capacitor (EDLC), ions are strongly adsorbed to the electrode surface. The ions that are specifically adsorbed are termed the inner Helmholtz plane (IHP), while the non-specifically adsorbed counter-ions form the outer Helmholtz plane (OHP). The capacitance of the device is directly proportional to the surface area of the electrode and inversely proportional to the distance between the two electrodes. This relationship highlights the importance of electrode surface area and the effective separation of charges in determining the performance of EDLCs. [80].:

The double-layer capacitor is a key characteristic of the electrical double layer that forms at the interface between a conductive electrode and an adjacent liquid electrolyte. The capacitance of an electrical double-layer (EDL) supercapacitors is calculated in a

manner similar to that of a parallel-plate capacitor, where the capacitance is determined by the surface area of the electrode, the dielectric constant of the electrolyte, and the distance between the electrodes. This fundamental relationship underlies the energy storage mechanism of EDLCs, allowing for efficient charge storage and rapid discharging.

;

$$C=\frac{\varepsilon_o \varepsilon_r A}{d} \qquad (3)$$

Where □*r* is the dielectric constant of the electrolyte, □*o* is the permittivity of vacuum, *A* is the surface area of the electrode accessible to the electrolyte ions, and *d* is the effective thickness of the EDL (i.e., the Debye length) [81]. The energy storage and discharge of the stored energy depends upon nanoscale charge separation at the electrochemical interface formed between an electrode and an electrolyte. During the storage of charge, the mechanism of storage of charge is non-faradaic. Further, there is no chemical oxidation-reduction (redox) are involved during charge storage. EDLCs have relatively long cycle lives because only physical charge transferring occurs [82].

b) Pseudocapacitors

Pseudocapacitors are a type of electrochemical energy storage device that utilize fast and reversible faradaic redox reactions to store charge, offering a hybrid between traditional capacitors and batteries by combining high power density with enhanced energy density. Unlike electrical double-layer capacitors (EDLCs) that rely on electrostatic charge accumulation, pseudocapacitors employ materials such as transition metal oxides (e.g., MnO_2, RuO_2), conducting polymers (e.g., polyaniline, polypyrrole), and metal sulfides, which participate in redox processes at or near the electrode surface. These materials enable higher specific capacitance and energy density but often face challenges related to cost, stability, and environmental impact. The performance of pseudocapacitors depends on factors such as electrode material properties, morphology, electrolyte selection, and device configuration, with nanostructuring

techniques being widely used to enhance surface area and ion transport. Due to their rapid charge–discharge capabilities and relatively high energy storage, pseudocapacitors are well-suited for applications in wearable electronics, regenerative braking, and portable energy systems. Ongoing research aims to improve their cycle life, energy efficiency, and cost-effectiveness, making pseudocapacitors a key focus in the development of next-generation energy storage technologies [83].

c) Hybrid supercapacitors:

Hybrid supercapacitors are advanced energy storage devices that combine the complementary advantages of electric double-layer capacitors (EDLCs) and pseudocapacitors or battery-type electrodes to achieve a balance between high power density, moderate to high energy density, and long cycle life. These systems typically integrate a capacitor-type electrode (often carbon-based materials such as activated carbon or graphene) with a battery-type or pseudocapacitive electrode (such as transition metal oxides, sulfides, or conducting polymers), allowing for enhanced electrochemical performance. The capacitor-type electrode offers fast ion adsorption/desorption processes, contributing to high power delivery, while the faradaic electrode provides higher energy storage through redox reactions. This asymmetric configuration expands the voltage window and maximizes energy density beyond what is possible with symmetric EDLCs. Electrolyte selection, electrode balancing, and material compatibility are crucial in optimizing hybrid supercapacitor performance, as mismatched kinetics or capacities can lead to reduced efficiency or cycle life. Nanostructuring and surface modification of electrode materials further enhance performance by improving ion transport and reaction kinetics. Hybrid supercapacitors are increasingly being explored for applications requiring both high power output and substantial energy storage, including electric vehicles, portable electronics, and renewable energy systems. Recent research focuses on developing cost-effective, environmentally friendly materials and scalable fabrication techniques to bring hybrid supercapacitor technology closer to commercial viability. With ongoing advancements in material science and device engineering, hybrid supercapacitors are positioned as a promising solution to the growing demand for efficient, durable, and high-performance energy storage systems across a wide range of sectors [84].

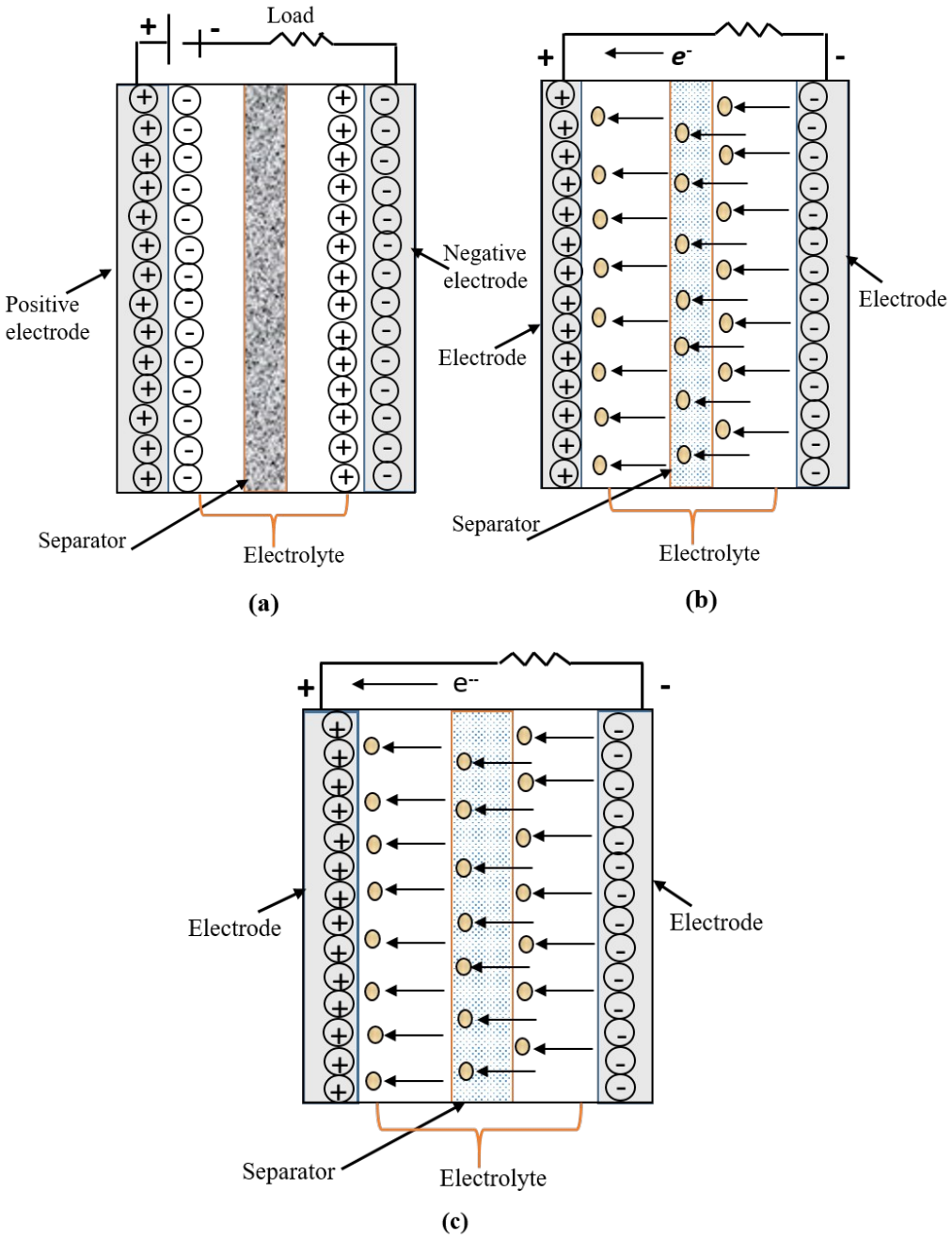

Fig. 4: Schematic representation of super-capacitor types: (a) EDLC type; (b) Pseudo-capacitor type; (c) Hybrid capacitor type [22]

The oxidation and reduction phenomenon takes place simultaneously in the super-capacitors. This phenomenon is based upon the famous Nernst equation. The term redox is derived from two words Red which stands for reduction and Oxi which stands for oxidation [85]. The emf of the cell can be calculated using Nernst equation.

$$E = E^0 - \frac{2.303\,RT}{nF}\log\frac{[¿]}{[Oxi]}$$

Where E° = the standard potential

R = universal gas constant

T = absolute temperature

F = Faraday constant

n = ion charge (moles of electrons)

Thus, the above equation signifies the amount of charge is a function of potential E. The charge discharge curve is the result of overlapping redox-reaction. The overlapping redox reactions gives charge-discharge curve. [85-86]. Adsorption of ions: The deposition of ions to form a monolayer on the electrode substrate is a reversible process that results in Faradic charge transfer and hence gives rise to pseudocapacitance in a similar manner as shown in redox reactions[66].

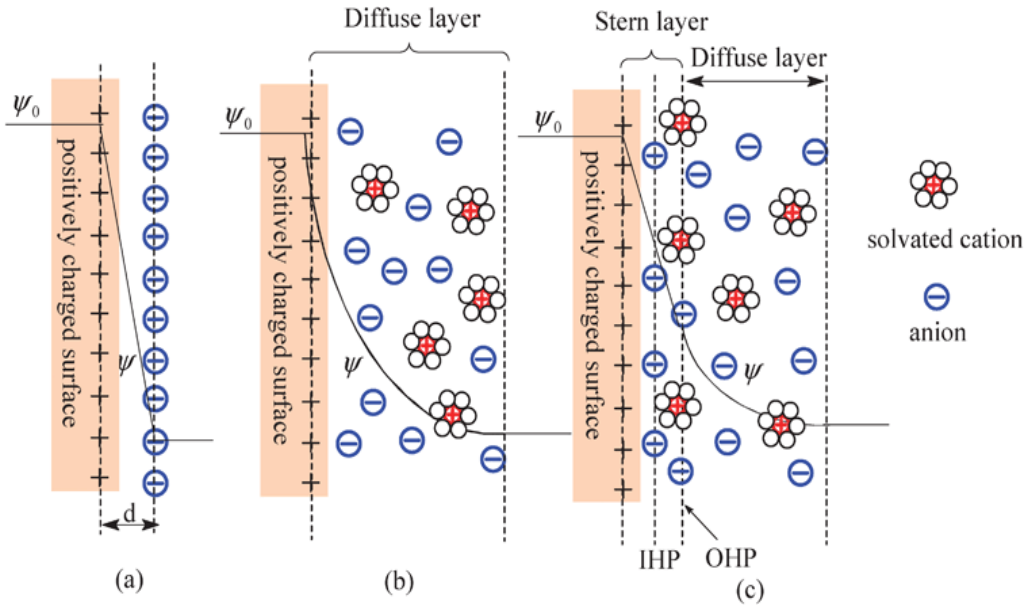

Fig. 5: Models of the electrical double layer at a positively charged surface: (a) the Helmholtz model, (b) the Gouy–Chapman model, and (c) the Stern model, showing the IHP and OHP.[22]

1.5 INSIDE THE Materials for Supercapacitors:

For the design and development of electrodes of super-capacitor, mainly two types of materials are used such as (1) Carbon based materials such as carbon nanotubes (CNTs), graphene, and activated carbon, and (2) Materials based upon metal oxides such as Ruthenium, Manganese, Copper, Cobalt, Nickel oxides and polymers like polyaniline (PANI) and polypyrrole (PPy), etc. The details of electrode materials related to their types are presented in Figure 6.

The another type of materials developed are composite materials obtained by combing two or more constituents of materials at nanoscale [87-88]. There is different possibility for the development of composite materials such as combing carbon nanotubes with conducting polymers or combing carbon nanotubes with metal oxide nanomaterials. When carbon nanotubes are combined with metal oxide nanomaterials, there is significant increase in surface area and hence there is enhanced capacitance performance. As a result, the synthesis and engagement of Nano-oriented resources are now recognized as a critical factor in developing the high performance of super-capacitor devices.

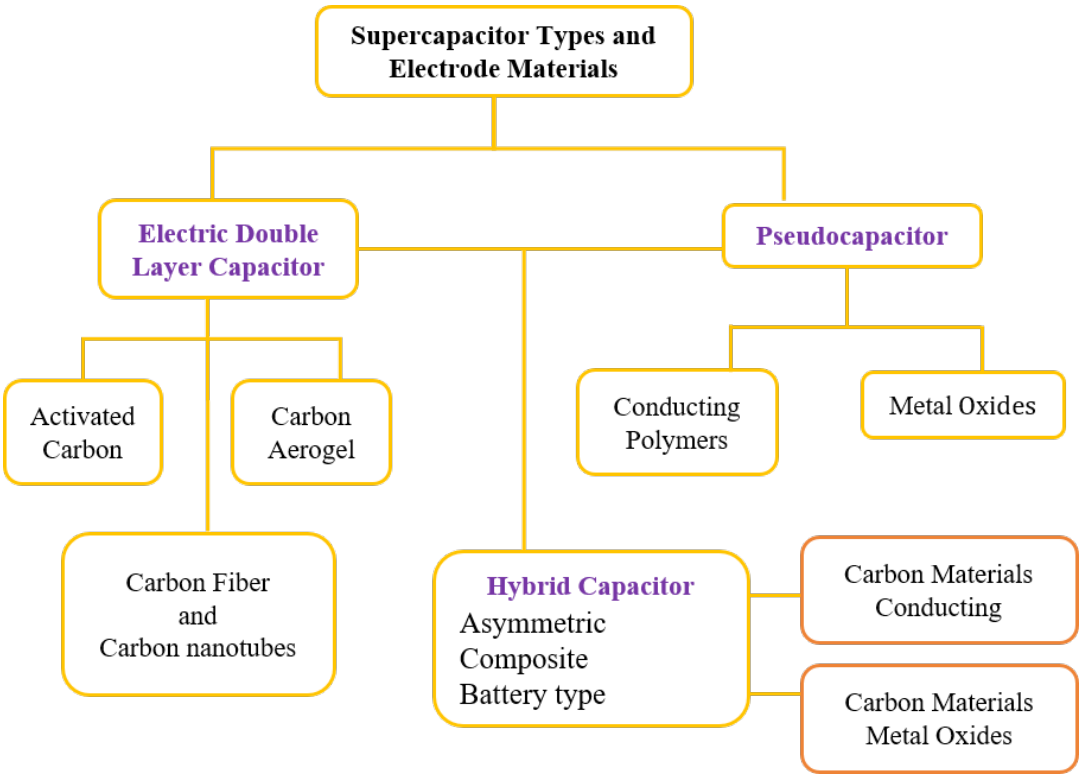

Fig. 6: Details of electrode materials based upon types of Super-capacitor [22]

1.5.1 The carbonaceous Materials in Super-capacitors for Veterinary Medicine:

Carbon is a chemical element symbolized C and having atomic number 6. This is the 15th most abundant element in the earth's crust. It is a reactive non-metal and tetravalent. The naturally occurring isotopes of carbon are C^{12}, C^{13}, C^{14}. Also carbon is found in several different allotropic forms such as diamond, graphite, charcoal, carbon nanotubes, Buckministerfullerene etc. The tubular form of carbon is known as carbon nanotubes which are having a diameter measuring on the nanometer scale Carbon nanotubes are formed from graphite sheets, and the graphitic Nanotubes are a member of the fullerene structure family [89-91]. Their name is derived from their long, hollow structure with the walls formed by one-atom-thick sheets of carbon called graphene. The new class of allotrope of carbon known as carbon nanotube was discovered bt Iijima in 1991 and are now considered a top-class subject in academic research and various industrial areas[68]. The developmental scenario for carbon nanotubes is illustrated in Table as below:

Table 4: Evolution of Carbon Nanotubes and their Applications in Super-capacitors

Year	Discovery
1952	Rudushkevich and Lukyanovich published a paper in the Soviet Journal of Physical

	Chemistry showing hollow graphite carbon fibers 50 nm in diameter .
1955	Hofer, Sterling and McCarney observed a growth of tubular carbon filaments of 10-200 nm in diameter
1958	Hillert and Lange observed a growth of nanoscale tubular carbon filaments from n-heptane decomposition on iron at about 1000˚C
1960	Bollmann and Spread borough discuss friction properties of carbon due to rolling sheets of graphene in nature. The electron microscopic examination clearly indicates formation of MWCNTs
1971	M. L. Lieberman reports growth of three different graphitic filaments, tubular, twisted and balloon like structure
1976	A. Oberlin, Morinobu Endo and T Koyama reported CVD growth of Nano-meter scale carbon fibres and they also reported discovery of carbon nanofibers including that some were shaped as hollow tubes
1979	John Abrahamson presented evidence of carbon nanotubes at the 14th Biennial conference of carbon at Pennsylvania state university
1981	A group of Soviet scientists published the results of chemical and structural characterizations of carbon nanoparticles produced by a thermodynamically disproportionation of carbon monoxide
1985	Fullerene was discovered
1987	Patent was sanctioned for graphitic, hollow

	core fibrils
1982	The continuous or floating catalyst process was patented by Japanese researchers T Koyama and Morinobu Endo
1991	Nanotubes were discovered in the soot of the discharge at NEC by Japanese researcher Sumio Iijima
1992	First theoretical predictions of the electronic properties of SWCNTs
1993	SWCNTs were discovered and methods to produce them was developed
1995	Electron emission properties of carbon nanotubes were discovered
1997	Carbon nanotubes were developed as optical antennas
1998	Carbon nanotubes-based field-effect transistors were developed
2000	First demonstration providing that bending carbon nanotubes changes their resistance
2001	A technique for separating semi-conducting and metallic nanotubes were developed
2002	MWCNTs were demonstrated as fastest known oscillators
2003	NEC announced stable fabrication technology for carbon nanotube transistors
2004	Nature journal published photo snap of SWCNTs
2005	Ideal carbon nanotube diode was developed
2006	Nanotubes were alloyed into carbon fibre bike that was ridden by Floyd Landlis Nanotubes were used as a scaffold for damaged nerve regeneration
2009	Nanotubes were incorporated in virus

	batteries Single walled carbon nanotubes were grown by chemical vapour deposition across a 10-micron gap in a silicon chip then used in cold atom experiments creating a black-hole like effect on single atom.
2012	IBM developed 9 nm nanotube transistor that outperforms silicon

Year	Discovery
1952	Rudushkevich and Lukyanovich published a paper in the Soviet Journal of Physical Chemistry showing hollow graphite carbon fibers 50 nm in diameter .
1979	John Abrahamson presented evidence of carbon nanotubes at the 14th Biennial conference of carbon at Pennsylvania state university,
1981	A group of Soviet scientists published the results of chemical and structural characterizations of carbon nanoparticles produced by a thermodynamical disproportionation of carbon monoxide
1991	Nanotubes were discovered in the soot of the discharge at NEC by Japanese researcher Sumio Iijima

Carbon nanotubes (CNTs) are carbonaceous nanomaterials that represent an allotrope of carbon, characterized by their cylindrical tube-like structures with diameters on the nanometer scale and lengths extending up to several millimeters. These structures exhibit

an exceptionally high aspect ratio, reaching up to 132,000,000:1, indicating a significant length relative to their diameter. CNTs are essentially rolled-up sheets of graphene that form hollow cylindrical tubes. Based on their wall structure, CNTs are classified into two main types: (1) Single-Walled Carbon Nanotubes (SWCNTs) and (2) Multi-Walled Carbon Nanotubes (MWCNTs). SWCNTs are typically synthesized in the presence of catalysts such as transition metals or metal oxides, whereas MWCNTs can be synthesized even without catalysts, making their fabrication comparatively easier. MWCNTs are further categorized into two structural models: (1) the armchair model and (2) the Russian doll model. CNTs have garnered extensive interest due to their unique structural, electrical, and mechanical properties, finding diverse applications across various fields, including their prominent use in supercapacitors for energy storage. Several synthesis techniques have been developed for CNT production, including (1) the arc discharge method, (2) laser ablation, and (3) chemical vapor deposition (CVD), each offering distinct advantages in terms of yield, quality, and scalability. These fabrication methods play a crucial role in determining the structural and functional characteristics of the resulting CNTs, which in turn influence their suitability for specific applications.

The mechanical strength of carbon nanotubes (CNTs) can be compromised by the introduction of structural defects, which may arise from atomic vacancies or the rearrangement of carbon bonds. Despite these potential weaknesses, CNTs are generally regarded as excellent thermal conductors, with the ability to transmit heat at rates of up to 6000 $W \cdot m^{-1} \cdot K^{-1}$ at room temperature. Both graphene and CNTs, as carbon-based nanomaterials, have garnered significant attention for their potential as high-performance electrode materials in supercapacitors design. This interest stems from their exceptional mechanical strength, large specific surface area, and, most importantly, their superior electrical conductivity. In addition to graphene and CNTs, other carbon-based nanomaterials such as

carbon aerogels, carbon fibers, activated carbon, and template carbon have been extensively explored for supercapacitors applications. These materials are commonly used as electrodes due to their abundance, low cost, and favorable porous structure, which facilitates efficient electrolyte diffusion into the electrode matrix. This permeability enhances ion transport and significantly boosts the capacitance of supercapacitors. The continued development and optimization of carbon-based nanomaterials remain a critical focus in the advancement of high-performance, cost-effective energy storage systems [92] .

In order to enhance the performance of the supercapacitors, different forms of carbon materials used as electrodes for electric double-layer capacitor**s** **(**EDLCs) are activated carbons, carbon aerogels, carbon fibers, and carbon nanotubes. Maximum specific capacitance value of different materials are shown below in Figure 7.

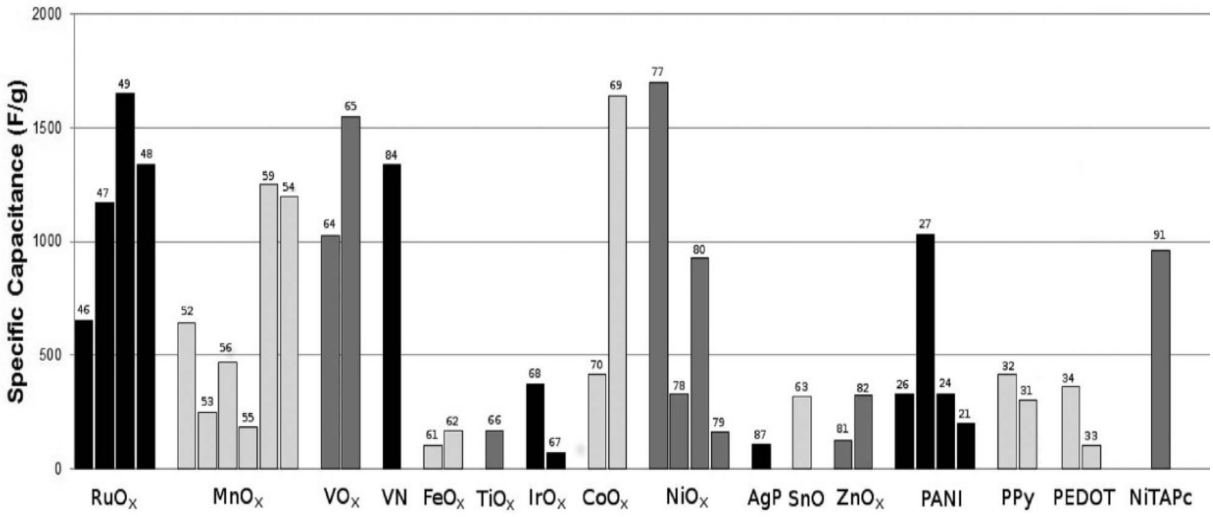

Fig. 7: Maximum specific capacitance values reported from the addition of different super-capacitive materials [22]

a) Carbon nanotubes (CNTs)

Until a few decades ago, only three allotropes of carbon—diamond, graphite, and charcoal—were widely known. However, with advancements in scientific understanding and the development

of sophisticated characterization techniques, several other carbon allotropes have since been discovered and extensively studied. These include carbon nanotubes, graphene, graphene oxide, fullerenes, and others. Each of these novel allotropes exhibits unique structural, electrical, and mechanical properties, making them highly valuable in a wide range of applications, particularly in nanotechnology, electronics, and energy storage systems. Their discovery has significantly expanded the horizon of carbon-based materials in modern science and engineering. [93]. Among various other allotropes of carbon and oxides of carbon, Carbon nanotube finds well known recognition amongst the group of researchers are scientists. Carbon nanotubes were discovered by Iijima in 1991. The cylindrical form of carbon is known as carbon nanotubes shows versatile applications. One of the possible applications of carbon nanotubes is in the fabrication of electrodes for super-capacitors [94].

Electrodes based on carbon nanotubes (CNTs) have been extensively developed due to their unique and advantageous properties, including a highly accessible external surface area (SSA), an internal network of mesoporous, excellent chemical and thermal stability, superior electrical conductivity, and low mass density. Their mechanical flexibility and open network structure contribute to enhanced interconnectivity with active materials, enabling efficient charge transport and continuous distribution throughout the electrode. Carbon nanotubes are primarily categorized into two types: (1) Single-Walled Carbon Nanotubes (SWCNTs) and (2) Multi-Walled Carbon Nanotubes (MWCNTs). These nanotubes can be synthesized using a variety of methods, with Chemical Vapor Deposition (CVD) being among the most effective. Notably, CNTs synthesized on 3D porous nickel foam using a one-step CVD process have demonstrated significantly improved electrochemical performance, including lower equivalent series resistance (ESR), higher capacitance, and superior performance at elevated current densities. In fact, such CNT-based electrodes exhibited approximately 127% higher capacitance compared to those fabricated via conventional synthesis techniques. As one-dimensional (1D) materials with high porosity, CNTs are capable of accommodating polymers within their tubular structure, allowing them to function effectively as dielectrics. The charge storage capability of carbon nanotubes is comparable to that of traditional materials such as charcoal, positioning them as promising

candidates for next-generation supercapacitors electrodes. However, nanotubes can be arranged in a regular pattern that exposes a better suitable surface area [95]. CNT-based electrodes are often fabricated as intertwined networks, featuring an open and accessible mesoporous structure. These interconnected mesopores form a continuous network that enhances the specific surface area more effectively, facilitating efficient ion transport. One of the key advantages of carbon nanotubes over activated carbon is their lower equivalent series resistance (ESR), attributed to the ease with which electrolyte ions penetrate the mesoporous network. Additionally, CNTs serve as structural scaffolds that promote the uniform dispersion of metal oxides, thereby enhancing both pseudocapacitance and electric double-layer capacitance (EDLC). Such hybrid electrodes demonstrate higher specific capacitance (Cs) compared to electrodes composed solely of carbon materials, metal oxides, or conducting polymers. Recent developments have introduced composite materials based on PEDOT:PSS and CNTs, achieving specific capacitance values ranging from 85 to 150 $F \cdot g^{-1}$, energy densities (Ed) exceeding 0.92 $Wh \cdot kg^{-1}$, and power densities (Pd) in the range of 100 to 3000 $W \cdot kg^{-1}$. Similarly, composite electrodes such as Co_3O_4/CNTs and Co_3O_4/carbon nanofibers (CNFs) have been fabricated, offering improved electrical conductivity and significantly enhanced surface area. These advancements highlight the growing potential of CNT-based composites in the development of high-performance supercapacitors electrodes [96].

b) Activated Carbons

Granular activated carbons (GACs) are highly versatile adsorbents capable of selectively adsorbing a wide range of organic and some inorganic substances. Their use dates back centuries—from medicinal applications in ancient Egypt to the charred interiors of whiskey barrels. Owing to their high surface area, well-developed pore structure, and surface reactivity, activated carbons are widely used for purification,

dechlorination, deodorization, and decolonization in both liquid and vapor-phase applications. They are also cost-effective and environmentally friendly, making them ideal for industries such as water treatment, food processing, cosmetics, automotive systems, industrial gas purification, and the recovery of petroleum and precious metals, especially gold. Granular vapor-phase activated carbon was first widely used during World War I in military gas masks and later in solvent recovery systems. Due to their low cost, high surface area, and eco-friendly nature, activated carbons (ACs) have become the preferred electrode material for electric double-layer capacitors (EDLCs) over other carbon forms. Traditionally, AC is derived from the pyrolysis of plant-based organic materials, including coal, coconut shells, wood, sugarcane bagasse, soybean hulls, and nutshells. The preparation of activated carbon involves two main steps: carbonization and activation. Carbonization is performed through pyrolysis or gasification at elevated temperatures in an inert atmosphere to produce bio char, which is then activated to develop its porous structure and enhance adsorptive properties. [97]. However, due to environmental pollution and the finite reserve of fossil fuels, academics are considering biomass waste as a possible resource for the fabrication of AC. High surface area per unit weight or volume can make granular activated carbon an effective substrate for dispensing other materials in a manageable form. In powder form, activated carbon is extremely fine, with average particle size of only 20 microns and bulk density of 21.5. This extremely aeratable meaning the slightest air movement may cause the activated carbon powder to flight and settle as dust. This dust fluidizes, or takes on the properties of a liquid. Activated carbon dust will coat nearly anything it lads on, including machinery, clothing and skin. In powder form, some activated carbons are capable of creating a dust explosion. Activated charcoal is a powder made up of tiny and very "rough" particles and a low-density heap with many holes that looks like a sponge [98]. The surface area of even a thin layer of such a material is many times greater than a material like aluminum, letting many more charge carriers be deposited in any given volume. But, the charcoal is not a

better insulator; it still replaces the excellent insulators used in conventional devices, so in general, EDLCs can only use low potentials on the order of 2 to 3 V. Concerning the surface area of AC, the capacitance is directly proportional to the surface area, and calculation reveals that not all the high surface area contributes to the capacitance of the device. This discrepancy may be due to electrolyte ions that are very big that they cannot diffuse into smaller micropores. Large pore size correlates with higher power densities, and smaller pore correlates with higher energy densities. As of 2010, virtually all commercial supercapacitors use powdered activated carbon developed from coconut shells, and higher performance devices are made based on synthetic carbon precursors activated with potassium hydroxide [99]. The activated carbon can be obtained from various carbon-rich organic precursors. The obtained coconut shell-based activated carbon exhibit supplementary micro-pores than the one which is made from charcoal. The specific capacitance values for the activated carbon electrolytes in aqueous electrolytes is higher than in organic solution. Apart from this the activated carbon shows certain disadvantages such as low density.

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c) Carbon Aerogels

Aerogel is a completely artificial, ultralight solid material derived from a gel through supercritical extraction, eliminating the need for binders. This process results in materials with extremely low density and thermal conductivity. Among various types, carbon aerogels are particularly noteworthy due to their exceptional electrical conductivity and high surface area. This unique combination makes carbon aerogels highly suitable for applications such as supercapacitors, fuel cells, and desalination systems. A key area of interest in carbon aerogels is their potential to serve as high-surface-area electrical conductors. Owing to these properties, carbon aerogels are increasingly employed as electrode materials in supercapacitors. Typically, the electrodes in aerogel-based supercapacitors are composite structures consisting of non-woven carbon fiber paper coated with an organic aerogel. This composite is then subjected to

pyrolysis, enhancing its conductivity and surface characteristics. The resulting electrodes offer excellent performance in energy storage due to their lightweight nature, high conductivity, and large electrochemically active surface area. [100]. The carbon fibers provide structural integrity, and the aerogel provides the required large surface area. Carbon aerogels are nanoporous carbon consisting of a weighty class of carbon nanomaterials and three-dimensional hierarchical morphology [101]. Due to these properties, carbon aerogels can be used as electrode material for EDLCs. Carbon aerogels are designed from the continuous net of carbon nanoparticles with a mesoporous structure with no binding agent. Usually, lower ESR was found in the binder less electrode of carbon aerogels. It was found that reduced ESR, which yields higher power, is of curiosity for investigators working in SCs area [102]. The small aerogel SCs are being used as backup electricity storage in microelectronics. However, Aerogel capacitors can only work at a few volts. At higher voltages, ionize the carbon and damage the capacitor. According to a literature survey, carbon aerogel capacitors have achieved 325 J/g (90 W. h/kg) energy density and 20 W/g power density. Some aerogel electrodes manufactured by pyrolysis of resorcinol-formaldehyde aerogels are better conductors than activated carbons. They provide thin and firm electrodes representing mechanical and vibrational constancy for SCs for their application in the high-vibration environment. Recently, Ultrahigh-specific capacitance for super-capacitor has been achieved by nickel cobaltite/carbon aerogel composites [103].

d) Graphene

Until recently, supercapacitors primarily utilized activated carbon as the electrode material due to its large surface area for charge storage. However, these devices typically achieved only about 8–10 Wh/kg of specific energy. Graphene has since emerged as a significantly more promising alternative, offering specific energy values in the range of 50–80 Wh/kg. Graphene is a single atomic layer of graphite and is considered one of the most important carbon allotropes. It features a two-dimensional (2D)

structure composed of sp^2-bonded carbon atoms arranged in a hexagonal (honeycomb) lattice. This unique structure imparts exceptional electrical conductivity, mechanical strength, and a remarkably high surface area—surpassing even that of carbon nanotubes—making graphene highly attractive for supercapacitors applications. The increase in capacitance is attributed to graphene's high surface area, dense atomic lattice, and tunable interlayer spacing. Furthermore, integrating graphene with other functional materials can lead to synergistic enhancements in supercapacitors performance, enabling tailored properties and improved energy storage efficiency. [104]. This state that graphene has great potential as a super-capacitor electrode. Graphene-based ac line-filters on a large scale have been developed by Wu et al [105]. In recent advancements, graphene oxide (GO) has been reduced using patterned metal interdigitates and employed as an electrode material. Shao et al. developed a quasi-solid-state micro-supercapacitors (micro-SC) utilizing cellular graphene films as the active material and PVA/H_3PO_4 as the gel electrolyte, representing a new class of flexible energy storage devices. In this design, three-dimensional (3D) graphene films function both as high-performance electrodes and as ion reservoirs for the gel electrolyte. These 3D cellular graphene structures are typically fabricated through a freeze-casting-assisted filtration assembly method, offering excellent mechanical strength and flexibility. The resulting quasi-solid-state device demonstrated strong electrochemical stability, retaining approximately 89% of its initial capacitance after 1000 charge–discharge cycles under repeated bending from 0° to 120°. One of the key advantages of using graphene as an electrode material is the accessibility of both sides of its atomic-thin sheets to the electrolyte, significantly enhancing charge storage capacity. These findings clearly highlight the potential of graphene in the development of high-performance supercapacitors. Moreover, the versatility and performance of various carbon-based nanomaterials, including graphene, carbon nanotubes, and activated carbon, have made them highly suitable for fabricating electrodes in supercapacitors. These advanced energy storage systems can be effectively integrated into modern veterinary diagnostic tools and portable medical devices, where lightweight, flexible, and efficient power sources are essential.

Table No 5: Carbonaceous Electrodes for Super-capacitors

Material	Surface area	Pore volume	Heteroatom content	Measurement system	Capacitance	Energy density	Power density
N doped porous carbon nanotubes	1786.1	0.8157	N 2.10 0.711	6M KOH, 0.25Ag^{-1}	339	11.77	34.11
N/O/S-doped hierarchical porous carbon materials	3519.50	2.68	---	1M H_2SO_4, 1Ag^{-1}	549	12.7	-----
N-doped microporous carbon sphere	1478	0.76	N 8.71, O 7.89	6M KOH 1A g^{-1}	292	8.75	500
B/N co-doped carbon Nano-sheets	2362	1.448	N 3.1, B 0.5	1M Na_2SO_4, 0.5Ag^{-1}	235.6	30.1	225.1
Honeycomb like porous carbon foam	1313	0.716	N1.1, O 11.2	1M Na_2SO_4, 2mVs^{-1}	260	29.3	----
N/O doped hierarchal porous carbon nanorods	1882	---	N 8.1, O10.0	EMIMBF_4 0.2 Ag^{-1}	214	116.5	472

1.5. 2. Conducting Polymers (CPs) The polymer is a macromolecule or large molecule made up of repeat units called monomer covalently bonded together. The polymers were supposed to be insulators. With the advancement in the domain of science and technology later on it was observed that certain polymers are capable of conduction of charges. These polymers are called as conducting polymers. The conducting polymers are having functional groups that behaves as pseudo-capacitors. The conducting polymers are showing poor life cycle as compared with carbon based materials. Therefore, conducting polymers are gaining importance as a vital electrode material for pseudo-capacitor. These type of materials are advantageous due to good conductivity, facile synthesis process and cost effectiveness. Thus

we can conclude that one of the biggest advantages of conductive polymer is their processability, mostly by dispersion. These types of polymers are usually not thermoplastic, means, they are not thermos-formable. However, like insulating polymers, they are organic resources. They can provide high electrical conductivity but not show alike mechanical properties to commercially obtainable polymers. The conducting polymers can store electric charge not only in electrical double layer but also through a rapid faradic charge transfer. Therefore, the specific capacitance of polymers is always higher than those of electrical double layer cells constructed with carbonaceous materials. The polymers which substitute a carbon for another atom could not conduct. However, as per our knowledge of conjugated system the pi electrons are loosely bound, electron flow may be possible. However, as the polymer covalently bonded the material needs to be doped for electron flow to occur. Doping is either addition of electron or removal of electron from polymers. Once doping has occurred, the electron in the pi-bonds are able to jump around the polymer chain. Thus, the polymer chain having conjugated structure throughout the chain, so that there is resonating or free electrons for conduction. Such types are polymers are highly crystalline in nature and shows planar structure. Also presence of aromatic rings in the chain with continuous resonance enhances conductivity. Also the polymer molecule should be co-planar. As the electrons are moving along the molecule an electric current occurs. The conductive polymers are widely used capacitors, sensors and actuators, printed circuit boards and electroluminescence in the electronics and semi-conductor industry. The demand for super-capacitors manufactured with the help of conductive polymers is growing with the increasing trends for miniaturization in electronic devices.

Charged polymers: This is the technical term for a permanently charged polymers is an electret. Electrets are electrostatic analog to magnets. Internally the electrets may use internally-trapped

electrical charges or the polymer may have been melted and then cooled while in a strong electrical field.

In recent years conducting polymers has attracted the attention of researchers due to their great potential in supercapacitors. Despite these properties, the conducting polymers have not become so popular among researchers and industrialists due to drawbacks such as low stability and poor mechanical properties, which restrict their applications in the fabrication of supercapacitor devices—conducting polymers, which are more correctly identified as intrinsically conducting polymers. An electronic device emits electromagnetic frequencies that disrupt the frequencies of other devices and may affect their performance, cause damages leading to reducing their lifespan. CPs have attained considerable attention as they supply high specific capacitance (due to their redox behavior), rapid charge-discharge process, lesser cost than carbon-based material, and a low ESR value. Notably, the n/p type polymer configuration has enormous potential for high E_d and P_d . However, the dearth of proficient n-doped conducting material and less cycling stability has postponed the improvement of CPs pseudocapacitor. Conducting polymers are organic polymers that can conduct electricity. These compounds have metallic conductivity or may sometimes act as semiconductors, a desirable property for SCs electrode materials. Again, it was confirmed that the mechanical stress on the conducting polymers during the reduction-oxidation reaction bounds the stability of pseudocapacitors through many charge-discharge cycles. Basis of electrical conductivity: the conductivity of organic polymers is owed to many processes. Polymer-like polyethylene, the valence electrons are in sp^3 hybridized, and sigma bonding electrons have low mobility and do not contribute to the electrical conductivity of the materials. The critical feature of bond structure available in conductive polymers can be easily calculated with the tight-binding model. The use of polymeric materials in the fabrication of

electrodes for super-capacitors which can be used in modern veterinary diagnostic tools is as illustrated below:

Table No 6: Polymeric Electrodes for Super-capacitors in Veterinary Medicine

Materials	Electrolytes	Testing	Year
PANI	PVA/H_3PO_4	--------	2013
PANI/ graphene	1M H_2SO_4	Two electrode	2009
PANI/GO	0.5M H_2SO_4	Three electrode	2014
PANI/Rgo	1M H_2SO_4	Three electrode	2018
PANI/GO	1M H_2SO_4	Three electrode	2019

1.5.4 Transition Metal Oxide

The d block elements are known as transition metals. The oxides of transition metals are semiconducting in nature. The transition metal oxides of iron, vanadium, manganese, copper, tin and ruthenium are widely used in research and applications of pseudo capacitance. The primary valence of transition metals is generally more than one. The introduction of Nano material is revolutionizing super-capacitors allowing for greater storage capacity and more diverse application. Majority of the transition metals exhibit multiple oxidation states at a particular potential, and accordingly the material can be selected within an electrolyte potential window which can allow development of maximum potential. The transition metal based compounds are most common redox-active materials, which are used as electrode materials for

super-capacitors. The transition metal oxide is one of the alternative materials for super-capacitors electrodes with high energy and power owing to their higher specific capacitance and lower resistance in comparison with carbon material, as well as their high conductivity. Transition metal oxides/hydroxides are considered the best candidates as electrode materials for energy conversion and storage applications. With the advancement in nanoscience and technology, nanostructured materials have attracted the attention of researchers and academicians. This is because of the fact that the stractures are having large surface to volume ratio i.e. aspect ratio. Some materials that are not stable in the bulk form and do not exist in the ambient atmosphere may exist in a more stable state at the nanoscale. Specially transition metal oxide (TMO) nanoparticles have received wide attention for energy storage applications[124]. The transition metal or metal oxides exhibits much benefits over other type of materials such as :: (i) structural changes that allow the altering of lattice symmetry and cell parameters, (ii) a change in electrochemical behavior due to the quantum confinement effect, and (iii) change in surface properties leading to a drastic increase in the bandgap that influences the conductivity and the chemical activity of the nanoparticles (Immanuel et al., 2019). Fabrication of desired quality of PDPU 38/180. Higher pseudocapacitance than the EDLC carbon electrode materials. It is well established that properties of nanomaterials, like composition, crystalline phase, structural and morphological properties, and the surface and interface properties between the electrode and electrolyte, greatly influence the electrochemical performance in device applications[125]Another essential advantage of crystalline metal oxide is that its high conductivities allow charge propagation along with the lattice structures of thin surface layers. However, considerably lower conductivity is observed for amorphous hydrous metal oxides. The conductivity can be increased by crystallization. The process of

crystallization needs the removal of water which eliminates pore spaces[120]. Ruthenium oxide was the first metal oxide used for super-capacitor applications. Ruthenium is the rare earth metal and also toxic nature. As far as practical purpose applications are considered, Ruthenium is very costly. Thus, the researchers again involved in the search of another material which is less expensive and also non-toxic in nature. Thus, different transition metal oxides were tried, such as manages oxide, vanadium oxide, copper oxide, zinc oxide, cobalt oxide etc were developed by the researchers. Figure 8 depicts how double layer is developed on CP chain.

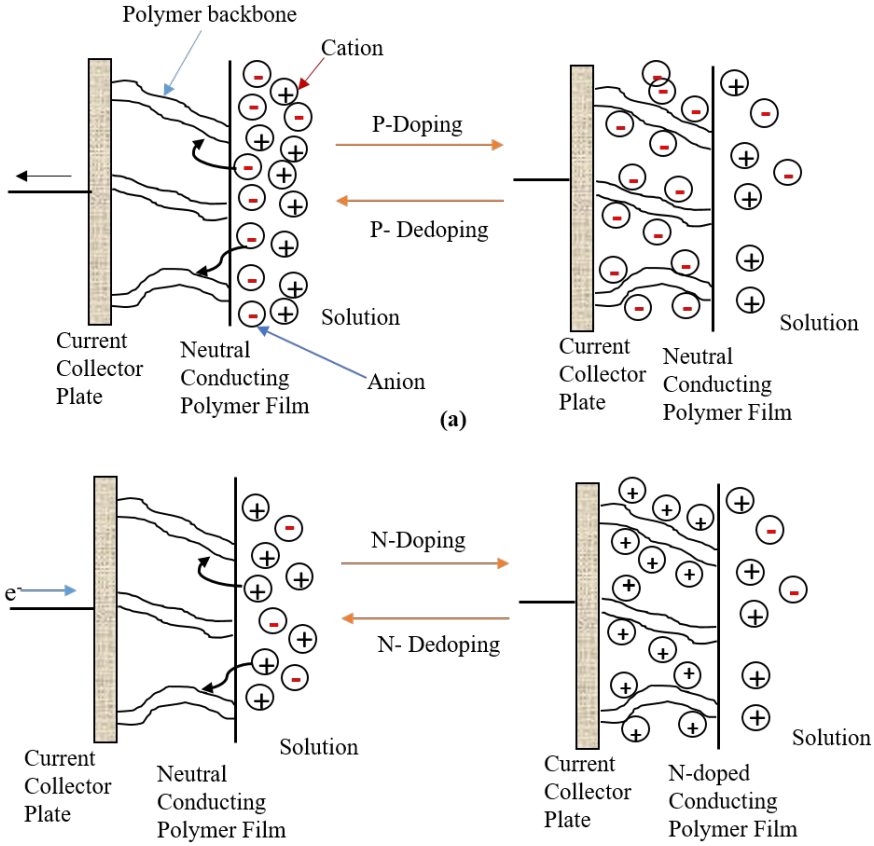

Fig. 8 (a) and (b) Development of double layer at CPs chain [22]

Here an attempt has been made to synthesize copper oxide nanoparticles dopping with different materials**.** Copper oxides exist in two stable forms, cuprous oxide Cu_2O and cupric oxide CuO. These two oxides have very different colors, crystal structures, and physical properties. The differences in such properties are due to differences in the oxidation state of transition metal copper. For

example, Cu_2O is reddish in color, cubic semiconductor, and displays interesting excitonic properties.

Table depicts the various types of materials used in the development of supercapacitors and their morphology and Csp.

Table No 7: Transition Metal Oxide Electrodes for Super-capacitors in Veterinary Medicine

Sr. No.	Material	Morphology	Csp (in Fg^{-1})	Reference
1	CuO			[107]
2	CuO	micro-woolen	346	[108]
3	CuO	rodlike morphology	300	[109]
4	hybrid CuO–PAA	Island like structure	136	[110]
5	CuO	well-adherent and porous cauliflower structure	36	[111]
6	CuO	Nanobuds	396	[112]
7	CuO/$Cu(OH)_2$ hybrid	Nanoflower (diameters-4-5µm)	459	[113]
8	CuO in [HPMIM][Cl] IL	nanobuds with bunch of nanopetals-like structure	60	[114]
9	CuO/$Cu(OH)_2$hybrid	Lotus like morphology	278	[115]
10	Ru doped CuO	Nanocrystal structure	406	[116]
11	CuO	Hierarchical multilayer nanosheets	43.	[117]
12	Hybride Cu-PAA	Circle like structures	65	[118]
13	CuO-PAA/CNT films	Circle like structures	258	[119]
14	CuO	Nanosheets	569	[120]
15	GN/macroCuO	macro-structured porous	417	[121]
16	CuO-GO	globular shaped nanoparticles	245 Fg^{-1}	[122]
17	CuO	Nanosheets arrays as well as flower like cluster	411	[123]

18	NSA–Ag/CuO	Nanosheets	689	[124]
19	CuO	nanowires and nanosheets and flower-like structure	212	[125]
20	CuS	Nanowire	305	[126]
21	Cu_2O/CuO/RGO	Nanoporous particles	136.3	[127]
22	CuO/N-RGO	unique particle–nanosheet structured	340	[128]

Nanosheet arrays were prepared by doping CuO nanosheet arrays using Ag by the silver mirror reaction. The specific capacitance of 689 Fg^{-1} at $1Ag^{-1}$ and 299 Fg^{-1} at $10Ag^{-1}$, respectively. Yunhu Li et al. revealed that nanostructured CuO nanowires and nanosheets and flower-like different morphology grown on copper foam substrate were prepared by thermal treatments for supercapacitors application. CuO nanosheets exhibited higher specific capacitance than nanowires, with a flower-like nanostructure of 212 Fg^{-1}. Yu-Kuei Hsu et al.revealed that hierarchical structures of wire-like CuS deposited on copper foil substrate using simple and cost-effective liquid-solid reactions. The high specific capacitance of CuS and NW nanoelectrodes is 305 F g^{-1}. Wang et al.[154] reported that Cu_2O/CuO/RGO nanocomposite was synthesized using the hydrothermal method on RGO nanosheets for supercapacitor application. The nanocomposite exhibited supercapacitor performance of 173.4 F g^{-1} at the current density of 1 Ag^{-1} and remained at 136.3 F g^{-1} at 10 A g^{-1} with the retention of 78.6%.

Moreover, the capacity remains 133.8 F g^{-1}, almost unchanged (98.2%) after 100,000 cycles at 10 A g^{-1}. Yiju Li et al. revealed that

the CuO/nitrogen-doped reduced graphene oxide (CuO/N-RGO) composites are prepared by refluxing in ammonia solution and low-temperature annealing. The CuO/N-RGO composite shows a high specific capacitance of 340 F g^{-1}.

P**roperties of Super-capacitors:** The remarkable properties of super-capacitors are as below:

* Super-capacitors have capacitance ranging from 1mF to 10kF.

* Super-capacitor have a high energy density of up to 10Wh/Kg

* There is less potential for pollution in super-capacitor as no heavy metals are used in their development.

*

1.6 Current Status of Transition Metal Oxides for Super-capacitors

1.6.1 Applications of Super-capacitors

1) Medical Applications of Super-capacitors: Sometimes in chronic disease conditions the internal organ do not work well and properly. The medication also do not respond properly. In such situation transplantation of internal organs is one of the possibility. But the internal organs are not manufactured in the laboratory. Hence we require a donor who can provide the internal organs. But we can not always get a proper donor. Also the transplantation of internal organ is the costly phenomenon. Therefore, some suitable devices are often planted into living organisms to perform the function of dysfunctional body parts. The fast technological development in biodegradable, implantable medical electronics have been achieved in recent years with advancement in material science. The reported implantable power sources are batteries, wireless power transfer modules and energy harvesters. However, most of these devices require a power supply to function appropriately. For instance, conventional batteries have been

integrated with the BIMEs to power them. Wireless power transfer device based on inductive coupling with coils has been shown to transfer electrical energy into the body from outside in an untethered manner. Triboelectrical energy generators have been demonstrated to efficiently harvest organs' mechanical motions into electrical energy. However, these devices have certain deficiencies, such as their nonbiodegradability, mechanical rigidity (incompatibility with soft organs and tissues), and relatively large form factors, thus limiting their usage as a biodegradable power source. On the other hand, a few recent studies on degradable batteries and supercapacitors have been reported to serve as biodegradable and bioabsorbable counterparts. However, some critical shortcomings exist. For instance, they are not proven or readily fully biodegraded and bioabsorbed within animal bodies, have relatively low electrochemical performances (energy and/or power densities), and/or have inappropriate form factors and are mechanically rigid, thus impeding the suitability of implantation. Therefore, fully biodegradable and bioabsorbable high-performance energy devices are sought. The batteries can be used as a power supply source, but they have a life span that will never be long enough, especially if they are implanted. Thus, the device needs to be brought out whenever batteries discharge, and the batteries need to be changed. Here, introducing a supercapacitor to the batteries or replacing the power is possible. The two organs in animal body produces electrical signals and they are brain and heart. The electrical signals produced by brain can be detected through electro encephalogram whereas the electrical signals produced from heart can be detected from electrocardiogram. The patients from cardiac disorders sometimes need pacemakers and other implantable electronic devices. These electronic devices need re-implantation once the batteries run out. When we observe the slow and steady development in the battery technology there is a big possibility for the harvesting electrical energy from the body

and using it to power implants. Therefore, the group of scientists at University of California Los Angeles and University of Cannecticut developed biological supercapacitor which can store electrical energy inside the body using benign and non-toxic components which are present inside the body fluid. The biological supercapacitors can be constructed using graphene sheets coated with protein produced by human body that can act as an efficient electrode. Here the single capacitor is micrometer thick and can be connected in bundles to provide more electricity storage. For the storage of charge, we are not using any external electrolyte. But the fluids present inside the body like blood serum or urine acts as electrolytes. The researchers tried to study the toxicity of the implanted devices and thus exposed mouse embryo fibroblast and culture of monkey kidney cells to material comprising the new capacitor, demonstrating no apparent toxicity.

.

The researchers hope that the new capacitors will be paired with an internal energy harvester, that uses heat or movement, to provide a reliable system for implantable medical devices.

Biosupercapacitor comprises graphene layered with modified human protein as an electrode, a conductor through which electricity from the energy harvester can leave. The platform could eventually also be used to develop next-generation implantable devices to speed up bone growth, promotes healing, or stimulates the brain.

How the biological supercapacitors work:

The biological Supercapacitor that the researchers invented uses charged particles of ions from bodily fluids to produce power. It uses electrolytes or ions present in body fluids such as blood, urine, and other extracellular biological fluids. It is possible that the supercapacitors can work with other devices known as energy harvesters.

2) Magnetic Resonance Imaging; This is a medical imaging technique. Here magnetic field and computer generated radio waves are used to create detailed images of organs and tissues of animal body. The magnetic field temporarily realigs water molecules present inside the animal body. The radio waves cause these aligned atoms to produce faint signals. These faint signals are used to create cross-sectional MRI images very much similar to slices in a loaf of bread. The MRI machines can produce 3D images also. This is the non-invasive way of diagnosis. This technique produces high resolution images inside the animal body that helps to detect the cause of illness. Today MRI is widely used to diagnose diseases and the etiology. This technique is widely used to diagnose[129]

* Aneurysms of cerebral vessels.
* Disorders of eye and inner ear
* Brain injury, hemorrhage and ischemia
* Multiple sclerosis
* Tumors

With the advancement of scientific knowledge special type of MRI called functional MRI was developed. This type of MRI produces images of blood flow in certain areas of brain. This can be used to examine the anatomy of brain and determine which part of brain are handling critical functions. Similarly, MRI of some internal organs like kidney, spleen, pancreas, uterus, ovaries and prostate is also possible.

(3) CT-Scan: This is the invasive diagnostic techniques which uses combination of X-Ray and computer technology to produce internal images. Traditional X-Ray machine use a fixed tube to point X-Ray at a single spot. As X-ray travel through the animal body, they are absorbed in different amounts by different tissues. Higher density tissue creates a whiter image than other tissues against the black background of the film. The X-ray produces 2D images

whereas CT-Scan produces 3D images. Sometimes veterinarians use a contrast agent. This contrast agent, sometimes called a dye, improves the image by highlighting certain features. The contrast can be sometimes orally taken or sometimes injected intravenously. The CT-Scan be used to detect internal injuries, internal bleeding, abnormal growth inside animal body. There are few side effects for the use of CT-Scan such as it can cause medical problems or allergic reactions. Most of the reactions are mild and results in rash or itchiness. Sometimes CT-Scan can damage the internal organs depending upon age, gender and parts of body to be scanned. Some organs are more sensitive to radiation than others [130].

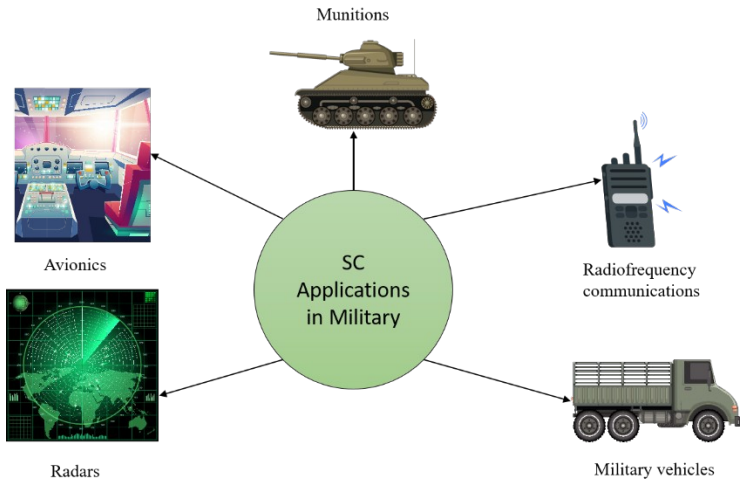

Fig. 9: Applications of Super-capacitors [22]

1.6.2 Advantages of Super-capacitor:

1. Very high efficiency.
2. Fast charging property
3. A super-capacitor has a longer life than a 10 to 15 years' battery
4. The Super-capacitor can withstand temperatures between -30 to 65 degrees centigrade, whereas a battery can withstand -10 to 40 degrees centigrade.
5. The Super-capacitor is very light in weight.

6. Super-capacitors can be installed in a short area as they are significantly smaller.
7. The Super-capacitor has a swift transient response.

Future Scope of Super-capacitors in Veterinary Medicine:

- **The** scope is very bright. In electronic system wearable electronics, as also medical implants, super-capacitors are coming up with solutions which The was never imagined before.
- **Robots w**ill find use of super-capacitors.
- **Super-capacitors** are used in regenerative breaking because they can charge very efficiently for high burst current.
- The super-capacitors will have wide range of applications in electronic devices.

Conflict of Interest

There are no conflicts of interest to declare.

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